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FINAL PROJECT

Topic: “Protection of LV system against lightning”

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I. Introduction

Lightning is a natural hazard and one of the greatest local mysteries. Scientists have not fully understood the mechanism of lightning. It is one of the most beautiful displays in nature and one of the nature's most dangerous phenomenon known to man.

Overvoltage due to lightning is a very important problem of LV systems. Some lightning flashes damage buildings and a few kill or injure people and animals, either directly or indirectly, by causing fire and explosions.

The need for protection, the economic benefits of installing protection measures and the selection of adequate protection measures should be determined according to IEC 62305.

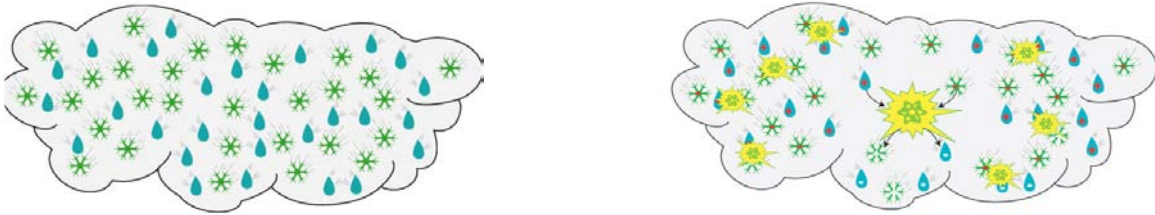
IEC 62305 is a standard that provides the general principles to be followed in the protection against lightning. It is based on scientifically proven theories and technical experimentation world-wide taking into account the international expertise in the matter. It includes 4 parts: general principles, risk management, physical damage and life hazards, and protection against electrical and electronic systems within structures. They lay down requirements for the design and installation of LPS for structures and buildings, the protection against lightning of services entering the buildings and the protection of electrical and electronic systems. On the basis of the standard IEC 62305 the current project presents the main conception of lightning and protection against it. This project presents the following stages:

- 1. What is lightning?**
- 2. Overvoltage mechanism between lightning and ground**
- 3. Overvoltage transmission through the structure and LV networks**
- 4. Protection measure**

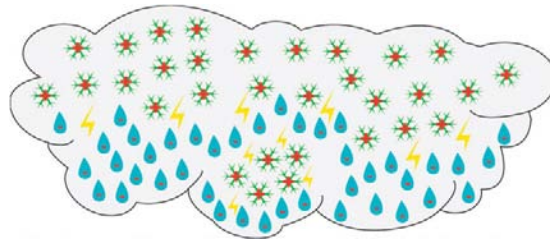
II. Lightning

1. Nature of lightning

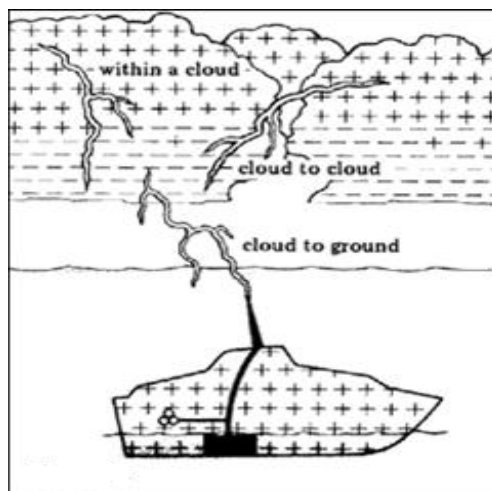
Lightning is a powerful natural electrostatic discharge produced during a thunderstorm. To put it simply, lightning is electricity. It forms in the strong up-and-down air currents inside tall dark cumulonimbus clouds as water droplets, hail, and ice crystals collide with one another.



Scientists believe that these collisions build up charges of electricity in a cloud. The positive and negative electrical charges in the cloud separate from one another, the negative charges dropping to the lower part of the cloud and the positive charges staying in the middle and upper parts.



Positive electrical charges also build upon the ground below. When the difference in the charges becomes large enough, a flow of electricity moves from the cloud down to the ground, or from one part of the cloud to another, or from one cloud to another cloud.



In typical lightning these are down-flowing negative charges, and when the positive charges on the ground leap upward to meet them, the jagged downward path of the negative charges suddenly lights up with a brilliant flash of light. Because of this, our eyes fool us into thinking that the lightning bolt shoots down from the cloud, when in fact the lightning travels up from the ground. In some cases, positive charges come to the ground from severe thunderstorms or from the anvil at the very top of a thunderstorm cloud. The electric current passing through the discharge channels rapidly heats and expands the air into a plasma, producing acoustic shock waves (thunder) in the atmosphere. The whole process takes less than a millionth of a second.

2. Types of Lightning

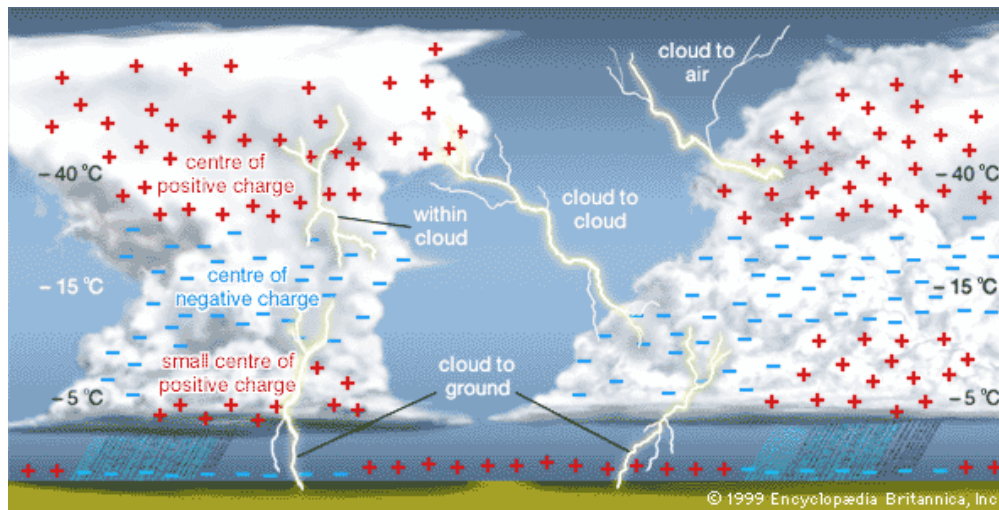


Fig. 1 Different type of lightning

. In generally the lightning can be divided into following basic types of lightning:

- **Cloud-to-ground lightning**



Cloud-to-ground lightning is a great lightning discharge between a cumulonimbus cloud and the ground initiated by the downward-moving leader stroke.

This is the most common type of lightning; it accounts for over 90% of the world-wide cloud-to-ground flashes. It is initiated by a downward leader lowering negative charge to earth.

- **Intra-cloud lightning**

Intra-cloud lightning is the second most common type of lightning which occurs completely inside one cumulonimbus cloud and jumping between different charge regions in the cloud .A type of intra-cloud lightning is commonly called an anvil crawler. Discharges of electricity in anvil crawlers travel up the sides of the cumulonimbus cloud branching out at the anvil top.



Intra-cloud Lightning



Anvil Crawler

- **Cloud-to-cloud lightning**



Cloud-to-cloud lightning is a somewhat rare type of discharge lightning between two or more completely separate cumulonimbus clouds

- **Ground-to-cloud lightning**

Ground-to-cloud lightning is a lightning discharge between the ground and a cumulonimbus cloud from an upward-moving leader stroke. Most ground-to-cloud lightning occurs from tall buildings, mountains and towers.



- **Cloud-to-Air Lightning**



Referring to a discharge (or a portion of a discharge) jumping from a cloud into clear air. Technically speaking, all cloud-to-ground lightning strikes contain 'cloud-to-air' components in the many branches that extend away from the main channel and terminate abruptly in mid-air. However, the most visually dramatic examples of cloud-to-air lightning occur when a long, bright lightning channel jumps out of the side of a cumulonimbus cloud and terminates in the clear air surrounding the storm.

According to Berger the lightning can be divided into the following types:

- Top left: downward negative
- Top right: upward positive
- Bottom left: downward positive
- Bottom right: upward negative

Cloud-to-ground lightning has been categorized by Berger in terms of the direction of development and the sign of charge of the leader that initiates the discharge (see Fig. 2).

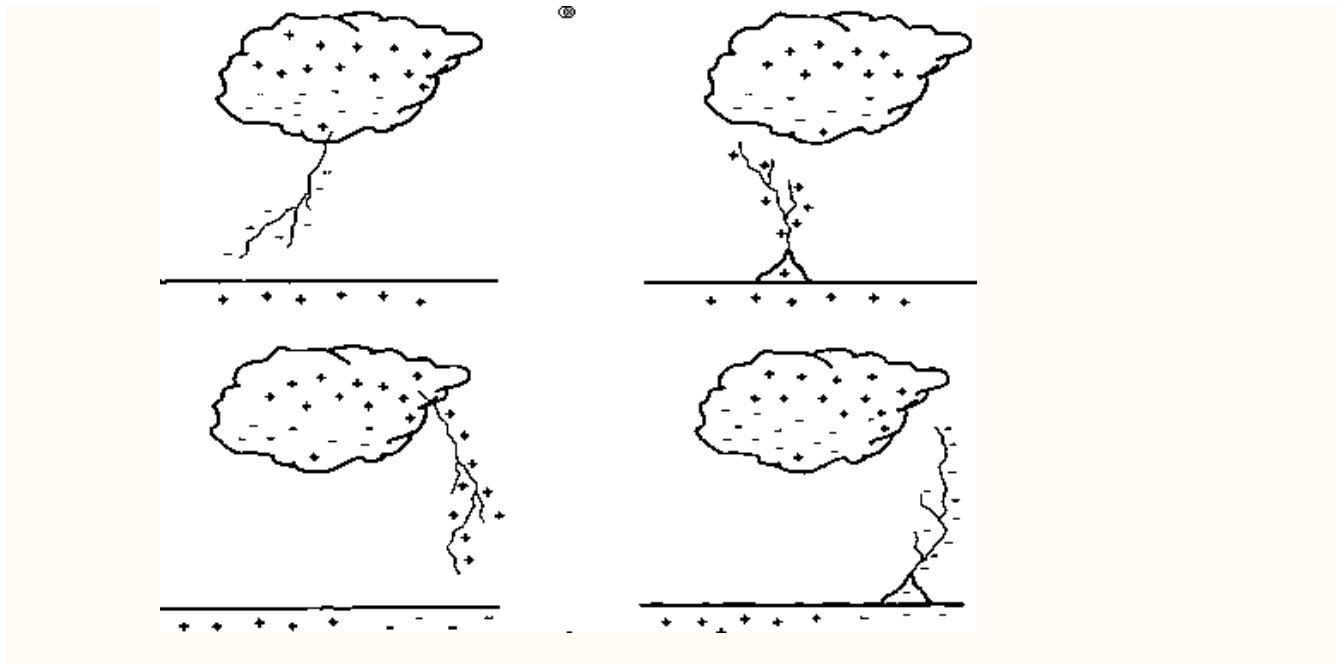


Fig. 2 Cloud-to-ground lightning categorization according to Berger

3. Lightning parameters

A lightning can be regarded as a current source, and the four lightning current parameters of concern in connection with design and dimensioning of lightning protection are: the peak lightning current (I), the steepness of the lightning stroke current impulses (di/dt), the charge transferred (Q) and the specific energy (W/R).

A lightning flash usually consist of several components. The whole event following the same ionized path is called lightning flash, which lasts up about 1s. The individual components of a flash are called short strokes and long strokes, which are more commonly known as continuing currents. Further differentiation of strokes comes from their polarity (positive or negative) and from their position during the flash (first, subsequent, superimposed).

The majority of lightning flashes are negative, making up about 90% of all cloud-to-ground flashes. Positive discharges make up the remaining about 10 % of all cloud-to-ground flashes. Normally the positive flashes exhibit the most powerful current parameters (i.e. higher I , Q , and W/R), while the negative flashes exhibit the steepest current impulses (i.e. highest di/dt).

Probability distributions of the electrical parameters that are used to describe a lightning stroke have been produced using direct measurements of actual stroke to tall towers. This statistical data on lightning current parameters is used in the lightning protection standards of the IEC 62305.

The probability distributions that describe the current parameters of a lightning are different for each type of lightning (upward/downward and positive/negative). The appropriate probability distributions are described below along with typical wave shape of each type of discharge. The probability level given indicates the probability of the specified current parameter of a particular lightning exceeding the tabulated value.

Two basic types of flashes exist:

- downward flashes initiated by a downward leader from cloud to earth;
- upward flashes initiated by an upward leader from an earthed structure to cloud.

3.1 Downward flashes

Mostly downward flashes occur in flat territory, and to lower structures, whereas for exposed and/or higher structures upward flashes become dominant. With effective height, the probability of a direct strike to the structure increases and the physical conditions change.

This type of lightning is divided into positive and negative lightning, depending on the polarity of the cloud charge.

- **Negative lightning**



A bolt of lightning usually begins when an invisible negatively charged stepped leader stroke is sent out from the cloud. When the two leaders meet, the electric current greatly increases.

An average bolt of negative lightning carries a current of 30 kiloamperes, transfers a charge of 5 coulombs, has a potential difference of about 100 megavolts, and lasts a few milliseconds.

Figure3 shows a typical profile of the lightning current in a negative cloud-to-ground flash. Following the contact of the stepped leader and the connecting leader, there is a first return stroke resulting (at ground) in a high amplitude impulse current lasting for a few hundred microseconds. Following the first return strokes, subsequent return stroke(s) and continuing current(s) may occur. Although subsequent return stroke generally have a lower current peak value and a shorter duration than the first return strokes, they generally have a higher rate of rise of current. It is possible for streamers to be sent out from several different objects simultaneously, with only one connecting with the leader and forming the discharge path. This type of lightning is known as negative lightning due to the discharge of negative charge from the cloud, and accounts for over 80-90% of all lightning.

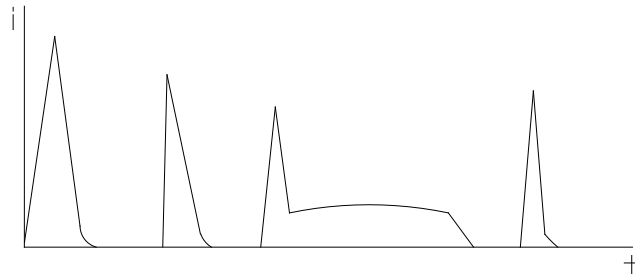


Fig.3 Typical profile of a negative cloud-to-ground flash (not to scale)

• Positive lightning



Positive flashes to ground generally occur less frequently than negative flashes, however in certain geographic locations there may be more positive flashes to ground. Present standards have assumed averages of 10% of flashes to ground are of positive polarity. In contrast to negative flashes, positive cloud-to-ground flashes are initiated by a continuously downward propagating leader which does not show distinct steps.

The connecting leader and return stroke phases are similar to the processes described above for negative flashes. It occurs when the stepped leader forms at the positively charged cloud tops, with the consequence that a negatively charged streamer issues from the

ground. The overall effect is a discharge of positive charges to the ground. As a result of their power, positive lightning strikes are considerably more dangerous. They tend to be 8 times more powerful than a negative strike, last about 10 times longer, strike several miles away from the storm and produce huge amounts of ELF and VLF radio waves.

Positive cloud-to-ground flashes are of great importance for practical lightning protection because the current peak value (I), total charge transfer (Q), and specific energy (W/R) can be larger compared to the negative first return stroke. A typical current profile for a positive cloud-to-ground flash is shown in Figure 4. Typical electrical parameters are summarized together with the parameters of negative discharge in Table 1.

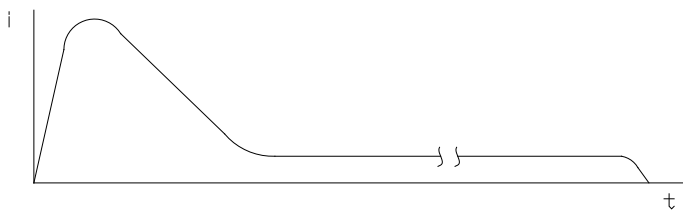


Fig.4 Typical profile of a positive cloud-to-ground flash

A lightning current consists of one or more different strokes according to IEC 62305:

- short strokes with duration less than 2 ms (Figure 5)
- long strokes with duration longer than 2 ms (Figure 6)

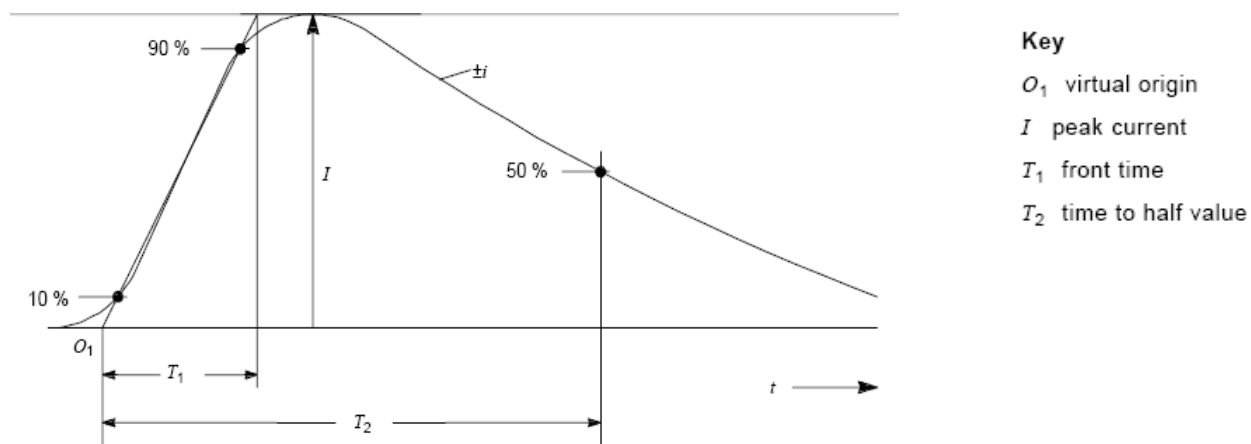
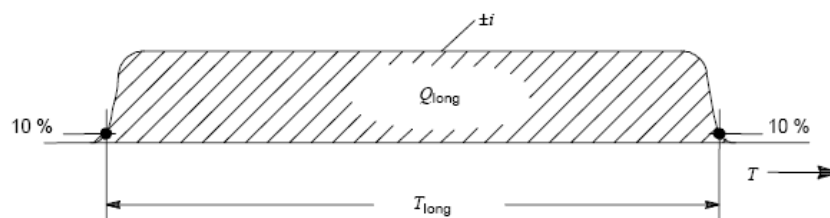


Fig.5 Definitions of short stroke parameters (typically $T_2 < 2 \text{ ms}$)



- Key**
- T_{long} duration time
 - Q_{long} long stroke charge

Fig.6 Definitions of long stroke parameters (typically $2 \text{ ms} < T_{\text{long}} < 1 \text{ s}$)

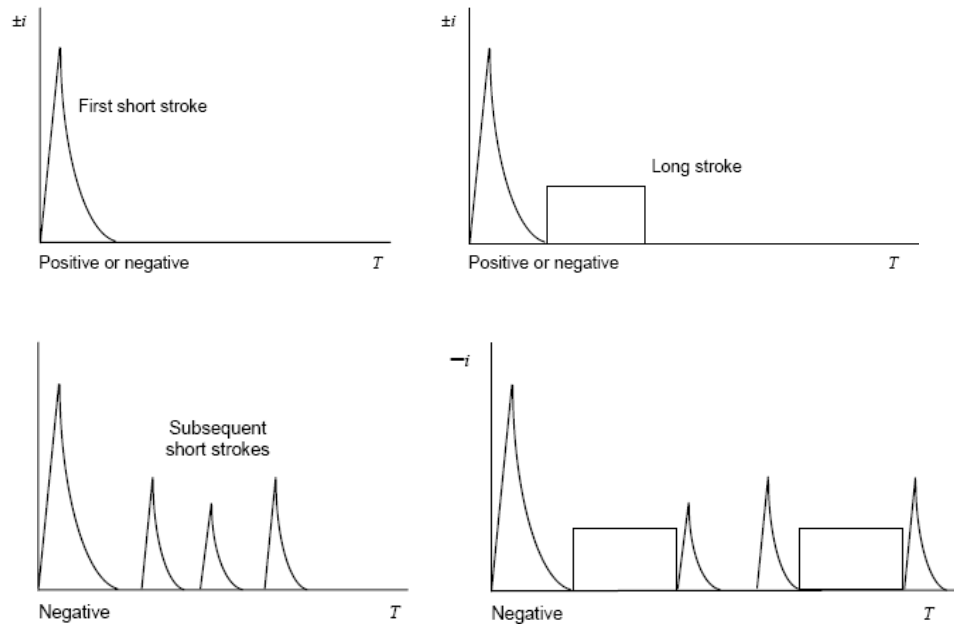


Fig. 7 Possible components of downward flashes (typical in flat territory and to lower structures)

Parameter	Fixed values for LPL I	Values			Type of stroke
		95 %	50 %	5 %	
I (kA)	50 200	4(98 %)	20(80 %)	90	*First negative short
		4,9	11,8	28,6	*Subsequent negative short
		4,6	35	250	First positive short (single)
Q_{flash} (C)	300	1,3	7,5	40	Negative flash
		20	80	350	Positive flash
Q_{short} (C)	100	1,1	4,5	20	First negative short
		0,22	0,95	4	Subsequent negative short
		2	16	150	First positive short (single)
W/R (kJ/ Ω)	10 000	6	55	550	First negative short
		0,55	6	52	Subsequent negative short
		25	650	15 000	First positive short
di/dt_{max} (kA/ μ s)	20	9,1	24,3	65	*First negative short
		9,9	39,9	161,5	*Subsequent negative short
		0,2	2,4	32	First positive short
$di/dt_{30/90\%}$ (kA/ μ s)	200	4,1	20,1	98,5	*Subsequent negative short
Q_{long} (C)	200				Long
t_{long} (s)	0,5				Long
Front duration (μ s)		1,8	5,5	18	First negative short
		0,22	1,1	4,5	Subsequent negative short
		3,5	22	200	First positive short (single)
Stroke duration (μ s)		30	75	200	First negative short
		6,5	32	140	Subsequent negative short
		25	230	2 000	First positive short (single)
Time interval (ms)		7	33	150	Multiple negative strokes
Total flash duration (ms)		0,15	13	1 100	Negative flash (all)
		31	180	900	Negative flash (without single)
		14	85	500	Positive flash

NOTE The values of $i = 4$ kA and $i = 20$ kA correspond to a probability of 98 % and 80 %, respectively

Table1 Cloud-to-ground lightning current parameters according to IEC 62305

3.2 Upward flashes



The charge in the thundercloud causes an elevation of the electric field on the surface of the earth, but usually not sufficient to launch an upward moving leader.

However, the electric field may be significantly enhanced at mountains, objects placed on high ground, or at tall structures like towers or wind turbines. At such locations the electric field strength may become large enough to initiate an upward moving leader from ground towards the thundercloud. Structures with heights in excess of 100m above the surrounding terrain are particularly exposed to upward initiated flashes.

An upward initiated flash starts with a continuing current phase. On the continuing current impulse, currents can be superimposed (Figure 8). The continuing current phase may be followed by subsequent return stroke(s) along the same channel. These return strokes are quite similar to the subsequent return strokes of cloud-to-ground flashes. Upward initiated flashes do not contain a component analogous to the first return stroke of cloud-to-ground flashes. The location where an upward lightning flash attaches to a structure is simply the same point where the upward leader is formed.

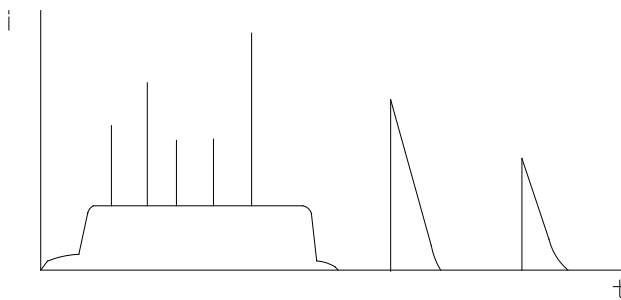


Fig. 8 Typical profile of a negative upward initiated flash

The following information on current parameters relates to upward negative flashes since, although observed, upward initiated positive flashes are rare.

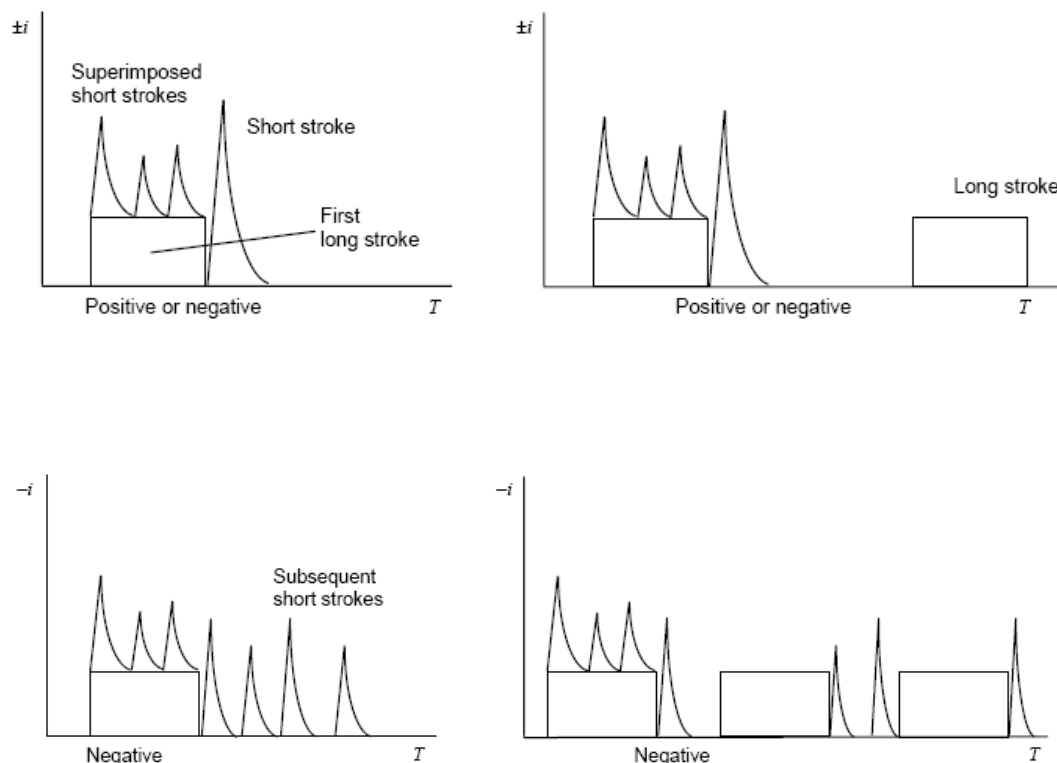
Although the current peak values of about 10kA are relatively low, the charge transfer associated with the initial continuing current has in rare cases been as high as 300C as shown in Table 2.

Parameter		Maximum value
Total charge transfer	C	300
Total duration	s	0,5 - 1,0
Peak current	kA	20
Average rate of rise superimposed impulse currents	kA/ μ s	20
Number of superimposed impulse currents		50

Table 2 Upward initiated lightning current parameters

Upward initiated flashes, too, may be composed of various combinations of the different current components mentioned above, as demonstrated in Figure 9.

In general, upward initiated flashes have lower current parameter values as compared to downward lightning flashes, possibly with the exception of the total charge transferred. Furthermore, it is evident that tall objects placed at exposed locations may experience very frequent upward lightning flashes, particularly during winter thunderstorms when tens of upward lightning flashes have been observed on very exposed tall objects.



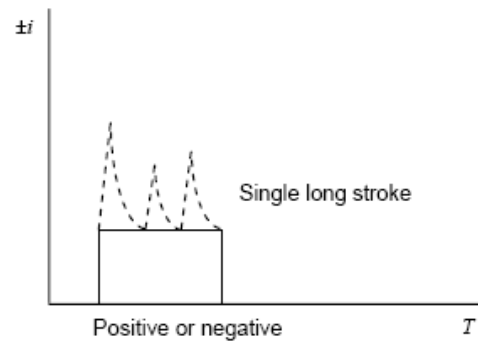


Fig.9 Possible components of upward flashes (typical to exposed and/or higher structures)

The additional component in upward flashes is the first long stroke with or without up to some ten superimposed short strokes. But all short stroke parameters of upward flashes are less than those of downward flashes. A higher long stroke charge of upward flashes is not yet confirmed. Therefore the lightning current parameters of upward flashes are considered to be covered by the maximum values given for downward flashes.

II. Overvoltage mechanism between lightning and ground

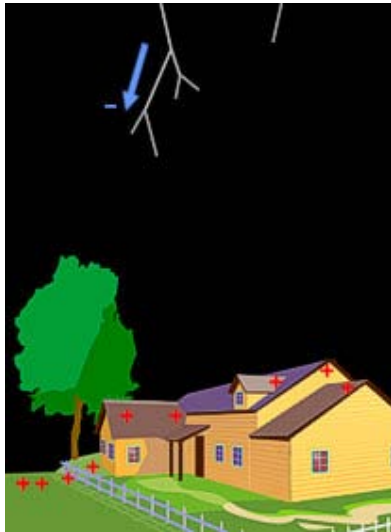
The overvoltage mechanism between lightning and ground is composed of a number of processes.

Cloud-to-earth lightning has the greatest damage potential.

Downward lightning discharges are discharges that are initiated in the cloud, initially develop in an overall downward direction, and transport charge to ground discharges.

The cloud-to-ground lightning flash can be considered into the next stages:

Step 1



A moving thunderstorm gathers another pool of positively charged particles along the ground that travel with the storm. As the differences in charges continue to increase, positively charged particles rise up taller objects such as trees, houses, and telephone poles.

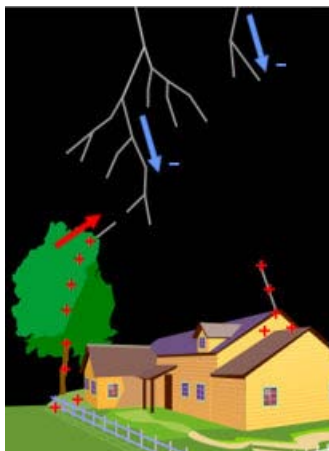
A typical cloud-to-ground lightning strike initiates inside the storm. Under the influences of the electric field between the cloud and the ground, a very faint, negatively charged channel called a "stepped leader" emerges from the storm base and propagates toward the ground in a series of steps about 50 meters (160 feet) in length and 1 microsecond (0.000001 seconds) in duration. The stepped leader is a small packet of negative charge that descends from the cloud to the ground along the path of least resistance. After a step, the leader pauses for about 50 microseconds, and then takes its next step. The stepped leader usually branches out in many directions as it

approaches the ground, carrying an extremely strong electric potential: about 100 million volts with respect to the ground and about 5 coulombs of negative charge.

Between each step there is a pause of about 50 microseconds, during which the stepped leader "looks" around for an object to strike. If none is "seen", it takes another step, and repeats the process until it "finds" a target.

It takes the stepped leader about 50 milliseconds (1/20th of a second) to reach its full length, though this number varies depending on the length of its path. Studies of individual strikes have shown that a single leader can be comprised of more than 10,000 steps.

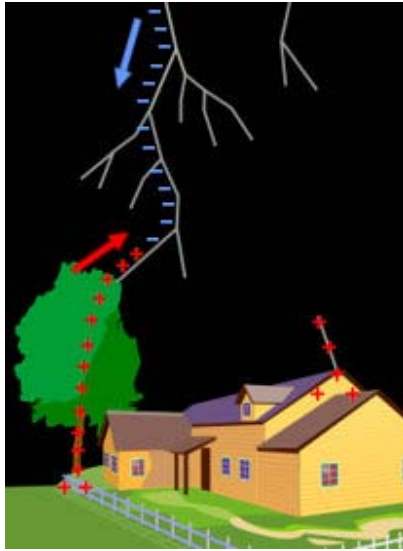
Step 2



As the stepped leader approaches the ground, its strong, negative charge repels all negative charge within the immediate strike zone of the earth's surface, while attracting vast amounts of positive charge. The influx of positive charge into the strike zone is so strong that the stepped leader actually induces electric channels up from the ground known as "streamers".

When one of these positively charged streamers connects with a negatively charged stepped leader (anywhere from 100 to 300 feet (30 to 100 meters) above the surface of the earth), the following steps occur in less than 100 microseconds.

Step 3



When a negatively-charged stepped leader finally connects with an area of positive charge on the ground, a continuous path between the cloud and the ground is established-attachment process. The electric potential of the stepped leader is connected to the ground and the negative charge starts flowing DOWN the established channel.

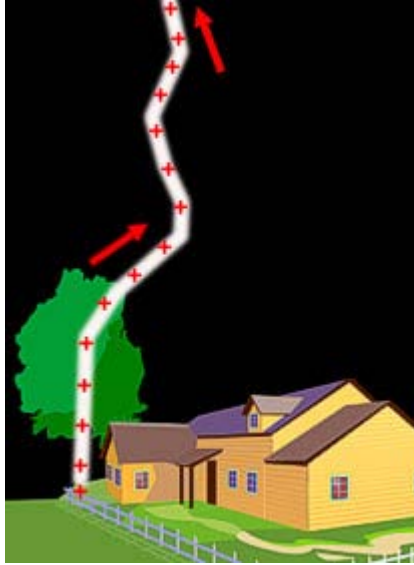
Step 4



When the step leader comes close to the ground, a strong electric field is created, which drives the positive charge on the ground to neutralize the negative charge in the path. The discharge releases an enormous amount of energy, and it is called the "returning stroke". The returning stroke is much brighter than the step leader, so what we see at lightning is a discharge which actually goes from the ground to the cloud. It takes the current about 1 microsecond to reach its peak value, which averages around 30,000 amperes. The returning stroke is much brighter than the step leader, so what we see at lightning is a discharge which actually goes from the ground to the cloud.

The "return stroke" produces more than 99% of a lightning bolt's luminosity and is what we see as lightning.

Step 5



After the return stroke ceases flowing up the channel, there is a pause of about 20 to 50 milliseconds. After that, if enough charge is still available within the cloud, another leader can propagate down to the ground. This leader is called a "dart leader" because it uses the channel already established by the stepped leader and therefore has a continuous path.

Dart leaders normally are not branched like the initial stepped leader. Not every lightning flash will produce a dart leader because sufficient charge to initiate one must be available within about 100 milliseconds of the initial stepped leader.

The dart leader carries additional electric potential to the ground and induces a new streamer from the ground. The dart leader's peak current is usually less than the initial stepped leader and its return stroke has a shorter duration than the initial return stroke. As additional dart leaders are produced, their peak currents and return stroke durations continue to decrease.

Dart leaders and their return strokes don't necessarily have to use the same cloud-to-ground channel that was burned by initial stepped leader. If a dart leader takes a different path to the ground, the lightning will appear to dance from one spot to another. This is known as "forked lightning".

III. Overvoltage transmission through the structure and LV networks

1. Causes of Transient Overvoltage

Lightning results from the potential difference between clouds or between a cloud and earth. Lightning strokes directly hitting the power system or indirectly inducing into it overvoltage via electromagnetic coupling are one of the main causes of power quality and electromagnetic compatibility problems. Overhead lines are extremely vulnerable to direct strokes or to induced voltage influences. Underground systems derived from aerial lines may also be affected.

Even if lightning protection and surge protection equipment is installed, a local lightning strike creates additional high magnetic fields, which in turn induce high voltage peaks in line systems. Inductive or galvanic coupling can cause damage within a radius of up to 2 km around the lightning impact point.

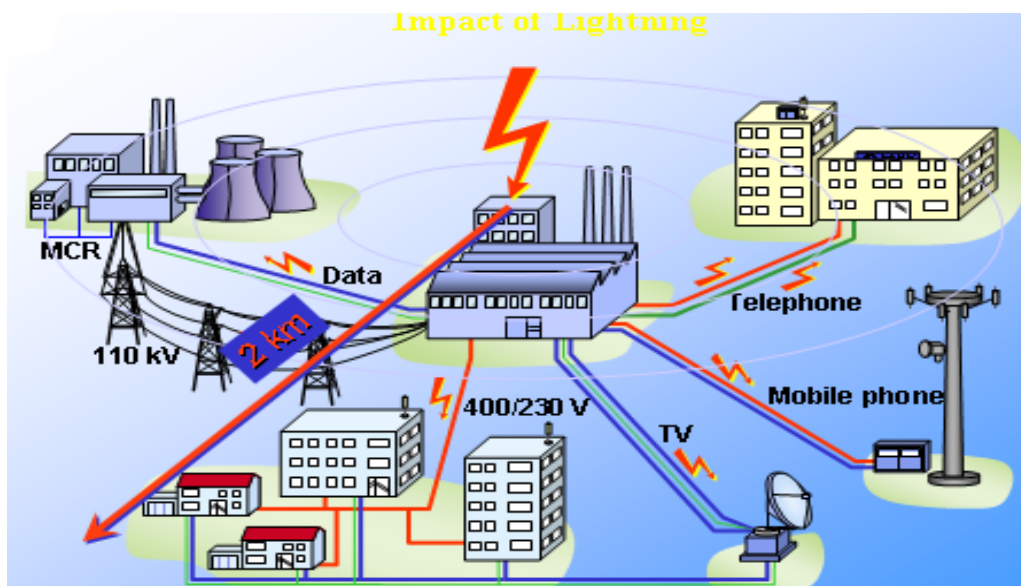


Fig.10 Impact of lightning

1.1 Atmosphere overvoltage

Lightning, as a source of interference, affects building and indoor electrical equipment and systems. Surge of atmosphere origin (Fig.11) are basically due to either a direct -/ close up strike or a remote strike. In the case of direct strike (Fig.11 case1a) , lightning strikes the protected building; but in the case of close – up strike, lightning strikes an extended system or a line(pipe line, date or transmission line) leading directly into the protected system. However, in the case of a remote strike (Fig.11 case 2 a) for example, the overhead line is struck. "Reflected surges" (traveling waves) are produced in transmission lines by cloud-to-cloud lightning, and overvoltage is induced by lightning in the surrounding area.

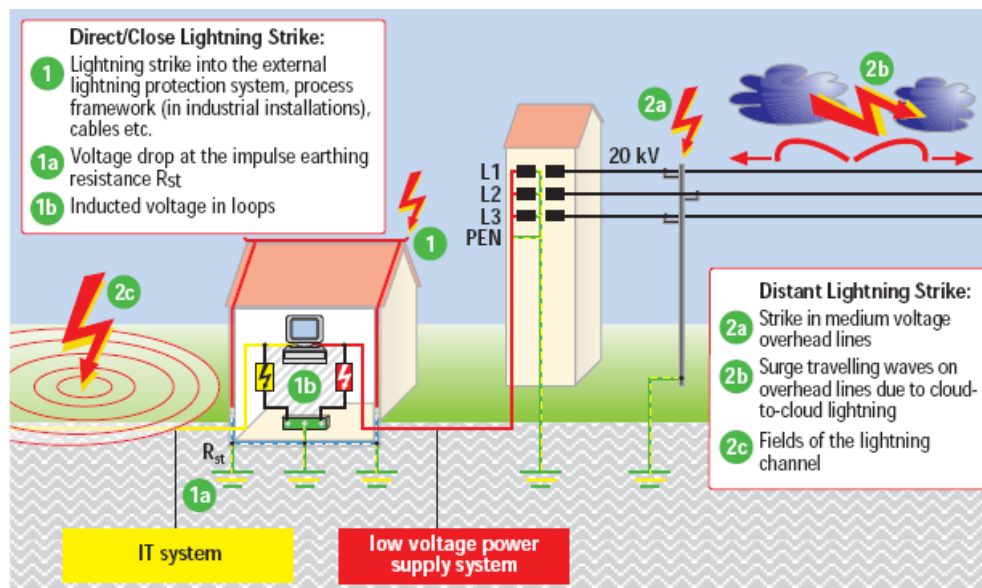


Fig.11 Types of atmosphere lightning overvoltage

a) Overvoltage due to direct and close-up strikes

Lightning can directly strike a building or a power or telecommunication overhead line. Direct or close lightning strikes are strikes into the lightning protection system of a structure, into its immediate surroundings or into the conductive systems entering in the structure (e.g. low voltage power supply, telecommunication and control lines...). Due to their amplitudes and energy loads, the arising impulse currents and impulse voltages represent a special risk for the system to be protected.

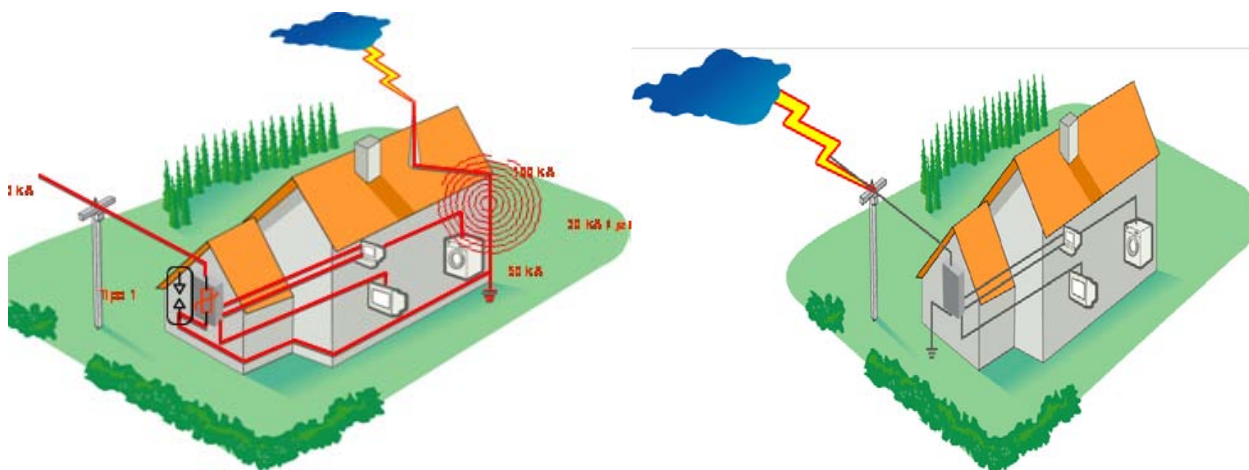


Fig.12 Direct lightning strike a) building and b) power line

Lightning current in a lightning channel and in the lines of lightning protection system causes a voltage drop at the impulse earth resistance of the earthing system (Fig.11, 1a) and induces surge voltages and currents in loops formed by installation lines inside the structure(Fig.11, 1b). Owing to the voltage drop at the impulse earth resistance, partial lightning currents also will be discharged by the supply lines that have been connected as a measure of lightning protection equipotential bonding.

A lightning strike in the surrounding area causes induced surge voltages and thus surge currents in installation loop especially due to its magnetic interfering radiation. If lightning strikes a feeding overhead line, there will be conducted surge voltage and currents on the incoming power line. Lightning between thunderstorm cells in clouds generates conducted surge voltages and currents on power lines and on other wide-ranging line systems due to interfering electromagnetic radiation.

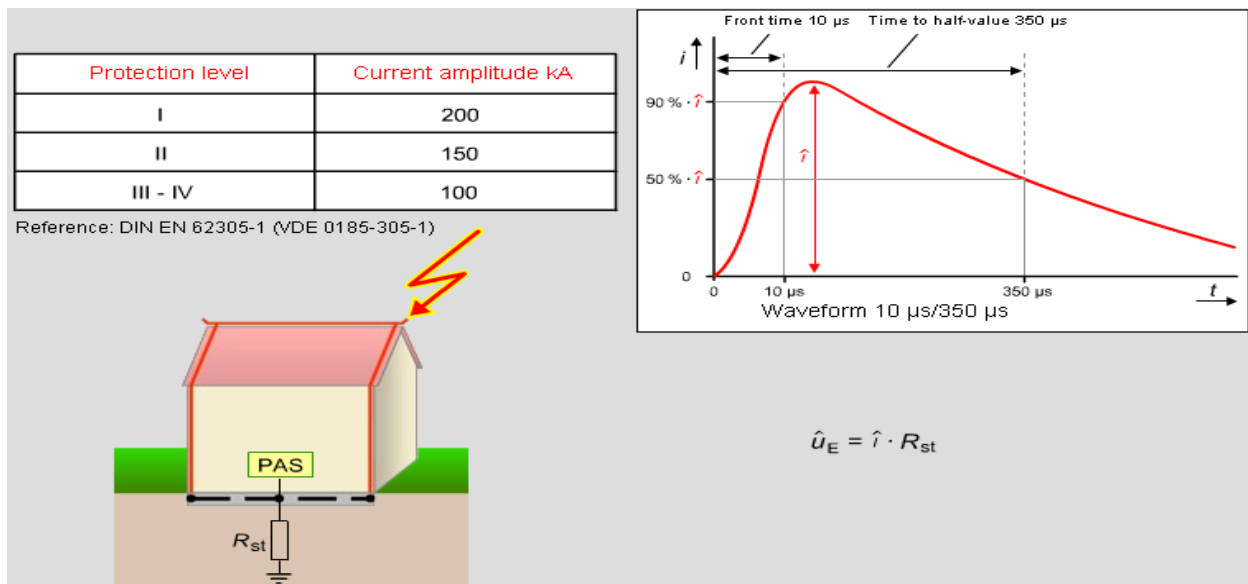


Fig. 13 Direct lightning current

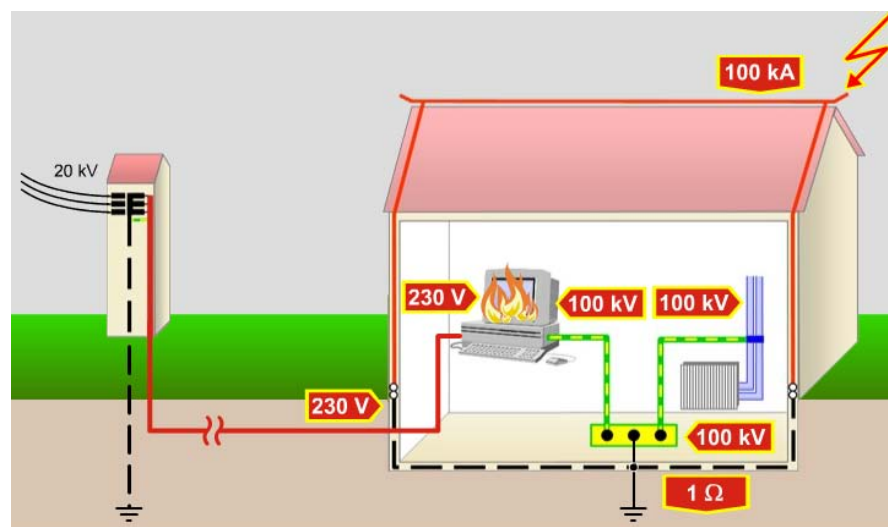


Fig.14 Direct lightning current, effects on a building

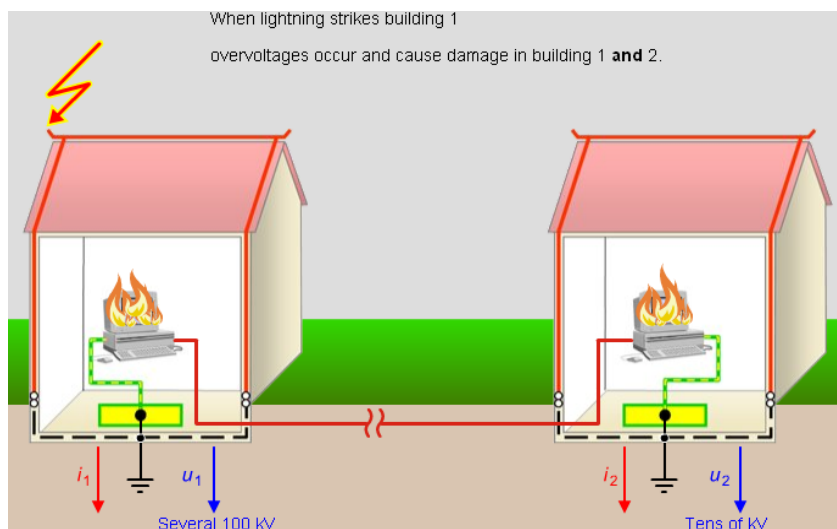


Fig.15 Direct lightning current, effects on several buildings

b) Overvoltage due to distant lightning strikes

Distant strikes are lightning strikes from a distance to the object to be protected, lightning strikes into the medium voltage overhead line network or into its immediate surroundings, or lightning discharges from cloud to cloud.

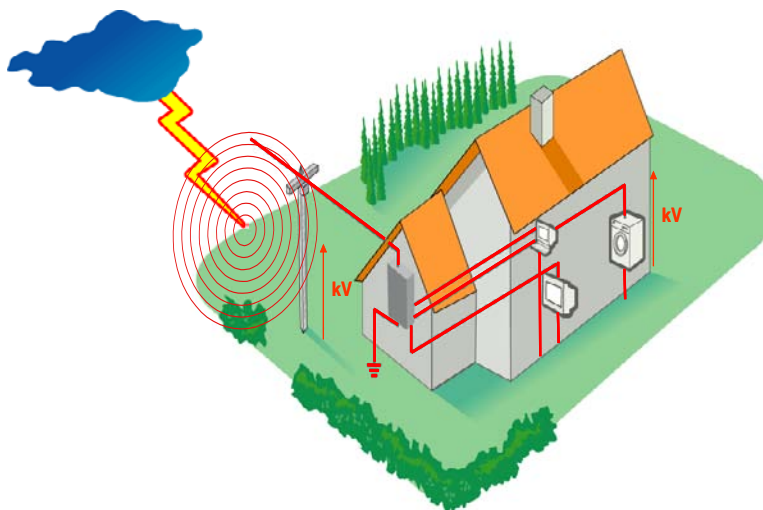


Fig.16 Indirect lightning strike

In analogy to induced surges, the effects of distant lightning strikes on the electrical system of a structure are controlled by devices and components, which are designed accordingly for impulse current wave $8/20\mu s$. In the case of remote strikes, travelling surges either propagate along the lines (Fig.11, 2a) or dangerous overvoltage are also produced by charges created between thunderclouds with different voltage potentials (Fig.11, 2b) or lightning strike(Fig.11, 2c) in the vicinity of the protected systems, thereby generating electromagnetic field which affect the system. Even if lightning strikes overhead cables several hundred meters away from a building or strikes an underground power supply cable through the roots of a tree, it can still produce overvoltage causing damage inside the

building. Surge voltages are entering the installation indirectly as a result of inductive or capacitive coupling. The inductive coupling occurs through the magnetic field of a live conductor. This magnetic field induces voltage peaks in nearby current loops. The capacitive coupling is the possible discharge of a voltage from one conductor to another in the case of large potential differences. These overvoltages are due to partial lightning currents entering the building via overhead cables or other cables.

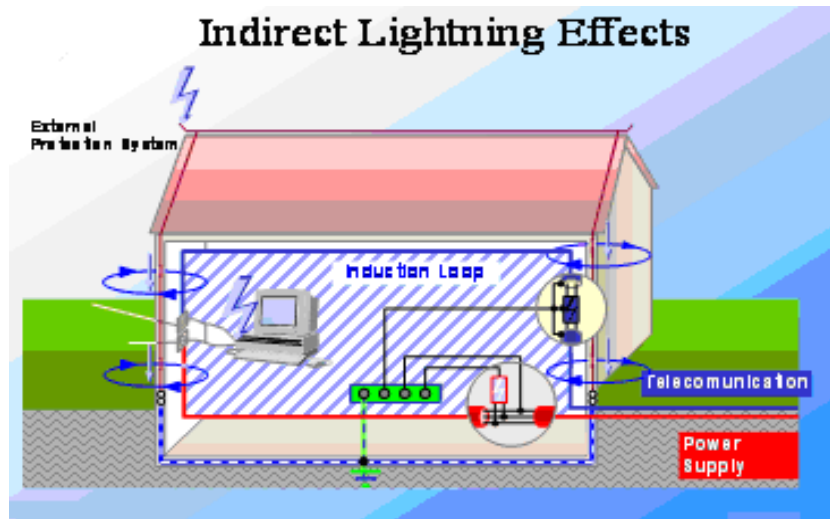


Fig17 Indirect lightning effects

When lightning partial currents flow in the cables they generate longitudinal and transverse voltage (Fig.18)

The longitudinal voltage u_l generated between the wire and the metal cable shield creates stress on the insulation of the connected device between its input terminals and the earthed enclosure. The transverse voltage u_q is established between the wires and this exerts pressure on the input circuit of the connected device.

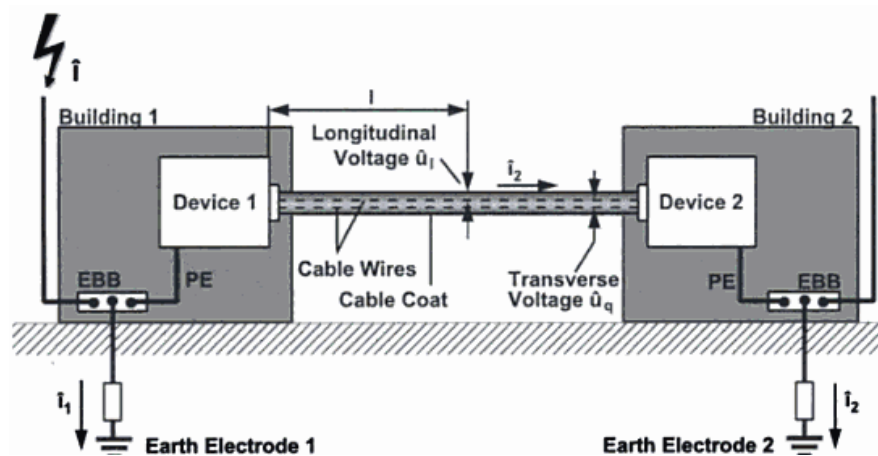


Fig.18 Surge in the cable

c) Coupling of surge currents on signal lines

The following examples will demonstrate how surge currents can be coupled ohmically, inductively and capacitively onto the signal lines of extended systems. Consider the arrangement with device 1 in the building 1 and device 2 in the building 2. The devices are interconnected by a signal line. Both devices are connected to respective equipotential bonding bar (PAS) in the building by means of protective conductors PE.

• Ohmic coupling

In the Fig.19 a lightning strikes building 1, causing a potential difference of some 100 kV at the ohmic earth resistance R_{A1} . A voltage of this magnitude is sufficient to sparkover the insulation distance in device 1 and device 2 so that an ohmically cross-coupled surge current can flow from PAS 1, through device 1, along the signal line, through device 2, PAS 2 and R_{A2} . The value of this surge current (it can have a peak value of several kA) depends on the relative values of the ohmic resistance R_{A1} and R_{A2} .

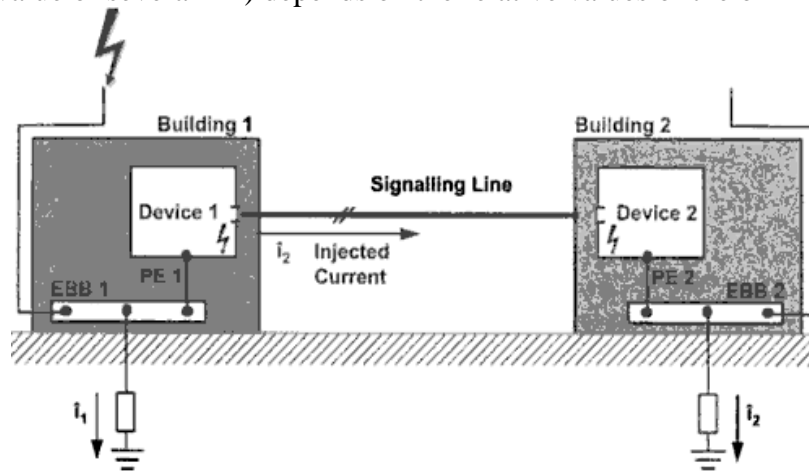


Fig. 19 Ohmic coupling

• Inductive coupling

As already shown, voltages are induced in metal loops by the inductive fields of lightning channel or the lightning current conducting lines.

Fig. 20 a) shows the two wire signal line between devices 1 and 2, forming an induction loop. A transverse voltage of several 1 kV will be coupled current of up to several kA. These voltages and currents stress the components at the inputs or outputs of equipment.

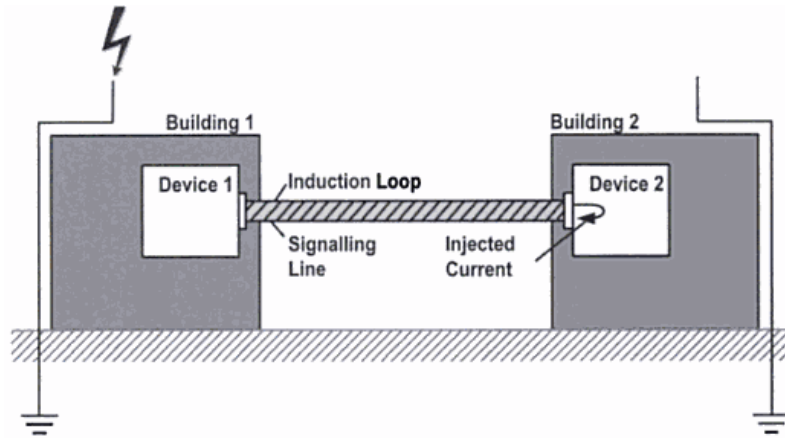


Fig.20 a) Inductive coupling: Induction loop between the wires of the signal line

Fig.20 b) shows another possible example of inductive coupling. The induction loop is formed by a signal line and the earth. If lightning strikes building 1, a high voltage (some 10 kV) will be induced in this loop leading to a sparkover of insulation distances in device 1 and 2 and to an uncoupled current of several kA.

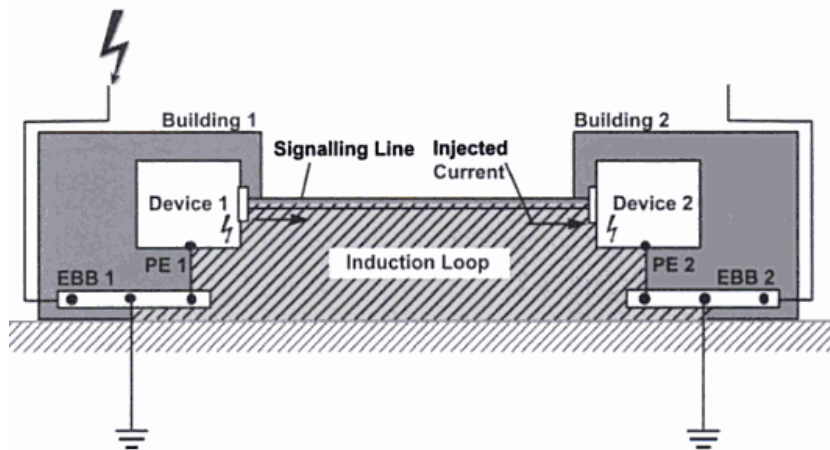


Fig. 20 b) Inductive coupling: Induction loop between line and earth

- **Capacitive coupling**

If lightning strikes the ground or a lightning conductor, the lightning channel or lightning conductor will be raised to a high voltage (some 100 kV) compared to the surroundings because of the potential difference at the earth electrode resistance R_A .

The signal line between device 1 and 2 in Fig. 21 is capacitively coupled with such a lightning channel or lightning conductor. The coupling capacities are charge and cause an “injected” current (some 10 A) which flows to the ground over the insulation distances in devices 1 and 2.

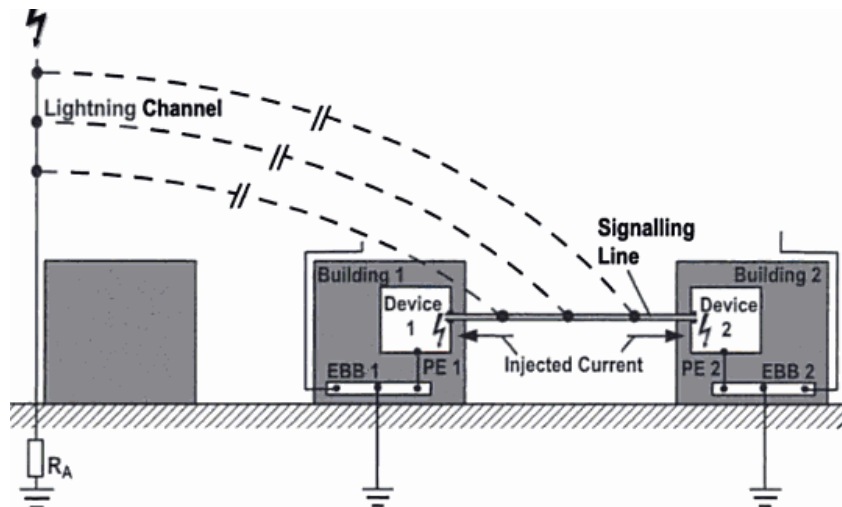


Fig.21 Capacitive coupling

- **Magnitude of atmosphere overvoltage**

Remote strikes initially cause of some 10kV. The generated currents are relatively low in value. Direct strikes, however, give rise to lightning currents of far greater and more severe magnitude: currents of 200 kA (protection level 1) and voltage peaks of 100 kV can occur.

Low-voltage installations can usually only withstand impulse breakdown voltages of several kV and therefore are susceptible to damage, or even destruction, by the tens of kV produced by remote strikes or 100 kV produced by direct strikes.

Therefore, these high values of overvoltage must be reduced to values which are clearly below the permitted impulse breakdown/spark over voltage by means of protective measure or surge protective devices.

1.2 Switching overvoltage

The overvoltage resulting from switching operations in public grids and low-voltage networks must not be underestimated, mainly because of their frequency.

The switching operations causing overvoltage include, for example, switching transformers and capacitors as well as other inductive loads on and off (e.g. welding transformers, fluorescent lamps) (Fig.22). Even power overhead lines, touching themselves occasionally due to poor installation and wind, can cause overvoltage.

As a rule, switching surges amount to two to three times the operating voltage, lightning surges on the other hand can sometimes reach 20 times the nominal voltage value and transport a high energy content. Often, failures occur only after a time delay as the aging process of electronic components in the affected devices triggered by smaller transients causes insidious damage. A number of different protection measures are required. These depend on the exact cause and/or impact point of the lightning discharge. Switching surges are caused by switch-on and switch off operations, by switching inductive and capacitive loads and by interrupting short-circuit currents. Particularly when production plants, lighting systems or transformers are switched off, electrical equipment located in close proximity can be damaged.

Overvoltages due to switching operations

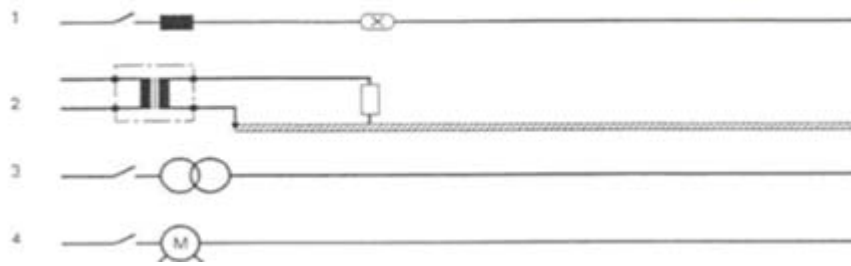


Fig.22 Switching overvoltage

2. Lightning current parameters relevant to the point of strike

The lightning current parameters playing a role in the physical integrity of an LPS are in general the peak current I , the charge Q , the specific energy W/R , the duration T and the average steepness of the current di/dt . Each parameter tends to dominate a different failure mechanism. The current parameters to be considered for tests are combinations of these values, selected to represent in laboratory the actual failure mechanism of the part of the LPS being tested. Table 3 records the maximum values of I , Q , W/R , T and di/dt to be considered for tests as a function of the protection level required, according with Standard series IEC 62305.

Component	Main problem	Lightning threat parameters					Notes
Air termination	Erosion at attachment point (e.g. thin metal sheets)	LPL	Q_{long} C	T			
		I	200	<1s (apply Q_{long} in a single shot)			
		II	150				
		III-IV	100				
Air termination and down conductor	Ohmic heating	LPL	W/R kJ/ Ω	T			Dimensioning with IEC 62305-3 renders testing superfluous
		I	10 000	Apply W/R in an adiabatic configuration			
		II	5 600				
		III-IV	2 500				
	Mechanical effects	LPL	I kA	W/R kJ/ Ω			
		I	200	10 000			
		II	150	5 600			
Connecting components	Combined effects (thermal, mechanical, and arcing)	LPL	I kA	W/R kJ/ Ω	T		
		I	200	10 000	<2ms (apply I and W/R in a single impulse)		
		II	150	5 600			
		III-IV	100	2 500			
Earth terminations	Erosion at attachment point	LPL	Q_{long} C	T			Dimensioning usually determined by mechanical/mechanical aspects (corrosion, etc.)
		I	200	<1s (apply Q_{long} in a single shot)			
		II	150				
		III-IV	100				
SPDs containing spark gaps	Combined effects (thermal, mechanical and arcing)	LPL	I kA	Q_{short} C	W/R kJ/ Ω	dI/dt kA/ μ s	Apply I , Q_{short} , and W/R in a single impulse (duration 7<2ms); apply dI/dt in a separate impulse
		I	200	100	10 000	200	
		II	150	75	5 600	150	
		III-IV	100	50	2 500	100	
SPDs containing metal-oxide resistor blocks	Energy effects (overload)	LPL	Q_{short} C				Both aspects need to be checked
		I	100				
		II	75				
		III-IV	50				
	Dielectric effect (flashover/cracking)	LPL	I kA	T			Separate tests can be considered
		I	200	<2ms (apply I in a single impulse)			
		II	150				
		III-IV	100				

Table 3 Summary of the lightning threat parameters to be considered in the calculation of the test values for the different LPS components and for the different LPL, according with Standard series IEC 62305

V. Protection measure

1. General

The lightning is dangerous event that has to be prevented by adequate protection measurements. Lightning flashes to, or nearby, structures (or services connected to the structures) are hazardous to people, to the structures themselves, their contents and installations as well as to services. This is why the application of lightning protection measures is essential. The protection against lightning, the economic benefits of installing protection measures and the selection of adequate protection measures is considered by International Standard IEC 62 305.

Protection measures may be adopted in order to reduce the risk according to the type of damage:

A) Protection measures to reduce injury of living beings due to touch and step voltages

Possible protection measures include:

- a) adequate insulation of exposed conductive parts;
- b) equipotentialization by means of a meshed earthing system;
- c) physical restrictions and warning notices.

B) Protection measures to reduce physical damage

Possible protection measures include:

- a) for structures
 - lightning protection system (LPS)
- b) for services
 - shielding wire

C) Protection measures to reduce failure of electrical and electronic systems

Possible protection measures include:

- a) for structures
 - LEMP protection measures system (LPMS) consisting of the following measures to be used alone or in combination:
 - earthing and bonding measures;
 - magnetic shielding;
 - line routing;
 - "coordinated SPD protection"
- b) for services
 - surge protective devices (SPDs) at different locations along the length of the line and at the line termination;
 - magnetic shields of cables.

2. Lightning protection system (LPS)

Complete system used to reduce physical damage due to lightning flashes to a structure.

Lightning protection systems are made of several different components, each having a specific function within the system. An LPS consists:

- ❖ External lightning protection systems
- ❖ Internal lightning protection systems

The functions of the external LPS are:

- to intercept a lightning flash to the structure (with an air-termination system),
- to conduct the lightning current safely to earth (with a down-conductor system),
- to disperse it into the earth (with an earth-termination system).

The function of the internal LPS is to prevent dangerous sparking within the structure, using either equipotential bonding or a separation distance s between the LPS components and other electrically conducting elements internal to the structure.

Class of LPS

The characteristics of an LPS are determined by the characteristics of the structure to be protected and by the considered lightning protection level.

Four classes of LPS (I to IV) are defined in this standard corresponding to lightning protection levels

LPL	Class of LPS
I	I
II	II
III	III
IV	IV

Table 4 Relation between lightning protection levels (LPL) and class of LPS

Each class of LPS is characterized by the following

- Data dependent upon the class of LPS:

- lightning parameters
- rolling sphere radius, mesh size and protection angle
- typical distances between down-conductors and between ring conductors
- separation distance against dangerous sparking
- minimum length of earth electrodes

- Data not dependent upon the class of LPS:

- lightning equipotential bonding
- minimum thickness of metal sheets or metal pipes in air-termination systems
- LPS materials and conditions of use
- material, configuration and minimum dimensions for air-terminations, down-conductors and earth-terminations
- minimum dimensions of connecting conductors

❖ External lightning protection system

1. General

- **Non-isolated LPS**

External LPS not isolated from the structure to be protected is LPS with an air-termination system and down-conductor system positioned in such a way that the path of the lightning current can be in contact with the structure to be protected.

In most cases, the external LPS may be attached to the structure to be protected.

When the thermal effects at the point of strike or on conductors carrying the lightning current may cause damage to the structure, or to the content of the structure to be protected, the spacing between LPS conductors and combustible material should be at least 0,1 m.

The positioning of external LPS conductors is fundamental to the design of the LPS and depends on the shape of the structure to be protected, the level of protection required and the geometric design method employed

- **Isolated LPS**

External LPS isolated from the structure to be protected is LPS with an air-termination system and down-conductor system positioned in such a way that the path of the lightning current has no contact with the structure to be protected.

An isolated external LPS should be used when the flow of the lightning current into bonded internal conductive parts may cause damage to the structure or its contents.

2. Application of an external LPS

The external LPS is intended to intercept direct lightning flashes to the structure, including flashes to the side of the structure, and conduct the lightning current from the point of strike to ground. The external LPS is also intended to disperse this current into the earth without causing thermal or mechanical damage, nor dangerous sparking which may trigger fire or explosions.

3. Choice of external LPS

In most cases, the external LPS may be attached to the structure to be protected.

An isolated external LPS should be considered when the thermal and explosive effects at the point of strike, or on the conductors carrying the lightning current, may cause damage to the structure or to the contents. Typical examples include structures with combustible covering, structures with combustible walls and areas at risk of explosion and fire.

4. Use of natural components

Natural components made of conductive materials, which will always remain in/on the structure and will not be modified (e.g. interconnected reinforced steel, metal framework of the structure, etc.) may be used as parts of an LPS.

5. Structure

5.1 Air-termination systems

5.1.1 General

The probability of structure penetration by a lightning current is considerably decreased by the presence of a properly designed air-termination system.

Air-termination systems can be composed of any combination of the following elements:

- rods (including free-standing masts);
- catenary wires;
- meshed conductors.

5.1.2 Design of air-termination system

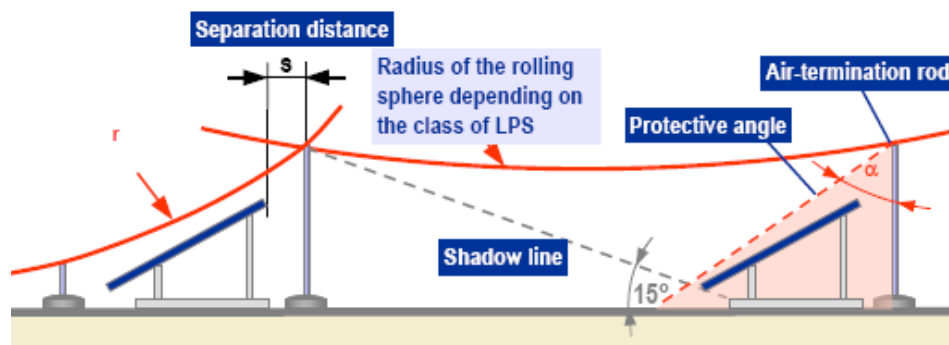


Fig.23 Design of air termination system

For the design of the air-termination system, the following methods should be used, independently or in any combination, providing that the zones of protection afforded by different parts of the air-termination overlap and ensure that the structure is entirely protected:

- protection angle method;
- rolling sphere method;
- mesh method.

All three methods may be used for the design of an LPS. The choice of class of LPS depends on a practical evaluation of its suitability and the vulnerability of the structure to be protected. The following considerations may be valid:

- the protection angle method is suitable for simple structures or for small parts of bigger structures. This method is not suitable for structures higher than the radius of the rolling sphere relevant to the selected protection level of the LPS;
- the rolling sphere method is suitable for complex shaped structures;
- the mesh method is for general purposes and it is particularly suitable for the protection of plane surfaces.

The values for the protection angle, rolling sphere radius and mesh size for each class of LPS are given in Table 5.

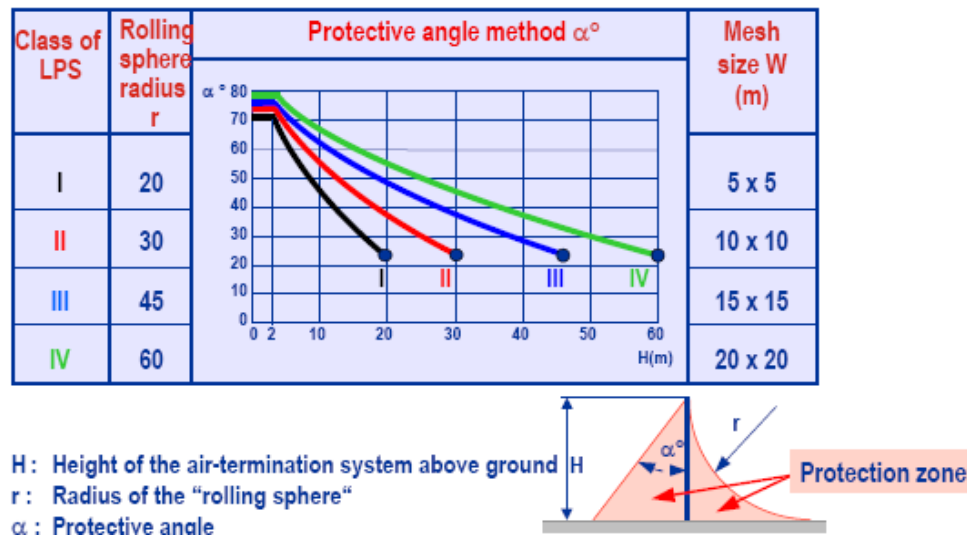


Table 5 Maximum values of rolling sphere radius, mesh size and protection angle corresponding to the class of LPS

5.1.3 Positioning

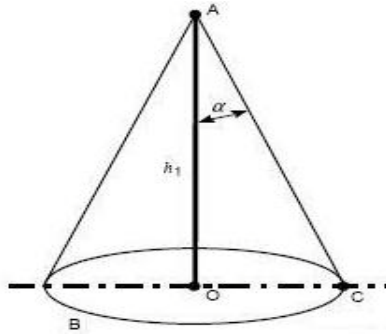
Air-termination components installed on a structure shall be located at corners, exposed points and edges (especially on the upper level of any facades) in accordance with one or more of the following methods.

a) Positioning the air-termination system when utilizing the protective angle method

The position of the air-termination system is considered to be adequate if the structure to be protected is fully situated within the protected volume provided by the air-termination system.

- **Volume protected by a vertical rod air-termination system**

The volume protected by a vertical rod is assumed to have the shape of a right circular cone with the vertex placed on the air-termination axis, semi-apex angle α , depending on the class of LPS, and on the height of the air-termination system as given in Table 5. Examples of the protected volume are given in Figures 1 and 2.



Key

A tip of an air-termination rod

B reference plane

O C radius of protected area

h_1 height of an air-termination rod above the reference plane of the area to be protected

Fig. 24 Volume protected by a vertical air-termination rod

- **Volume protected by a wire air-termination system**

The volume protected by a wire is defined by the composition of the volume protected by virtual vertical rods having vertexes on the wire.

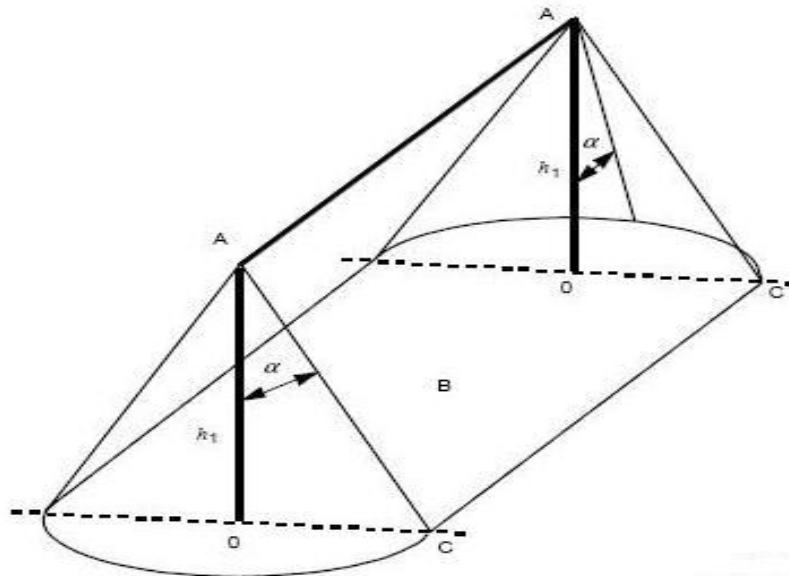


Fig. 25 Volume protected by a wire air-termination system

- **Volume protected by wires combined in a mesh**

The volume protected by wires combined in a mesh is defined by a combination of the protected volume determined by the single conductors forming the mesh.

Examples of the volume protected by wires combined in a mesh are given in Figures 26 and 27.

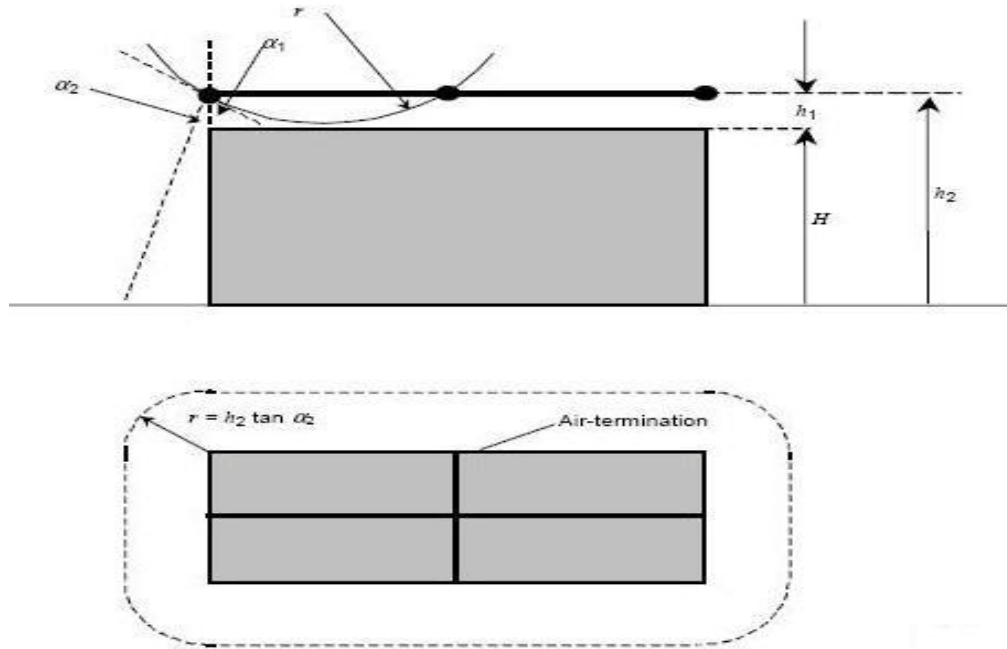


Fig. 26 Volume protected by isolated wires combined in a mesh according to the protective angle method and rolling sphere method

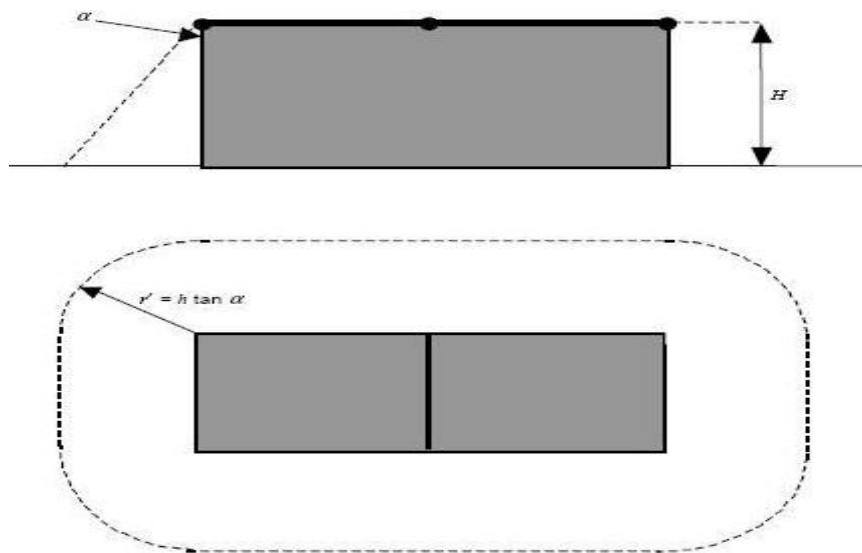
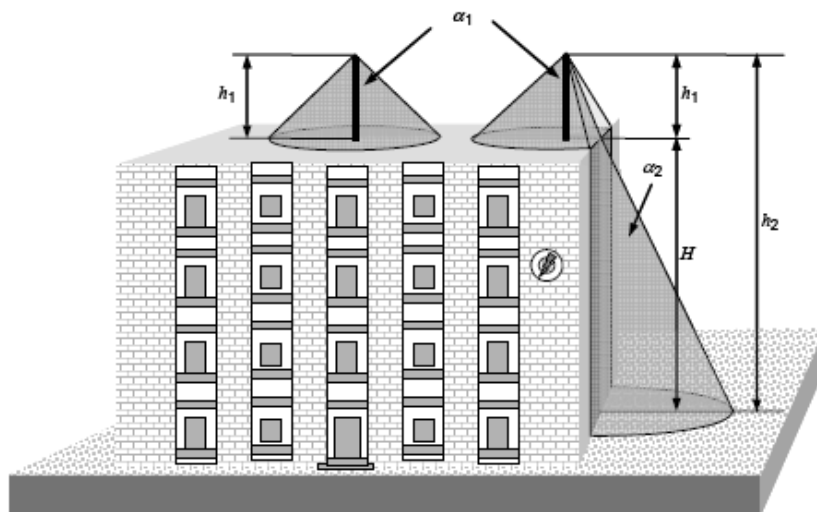


Fig. 27 Volume protected by non-isolated wires combined in a mesh according to the mesh method and the protective angle method

According to Table 5, the protective angle α is different for different heights of air-termination above the surface to be protected – figure 28



Key

H Height of the building over the ground reference plane

h_1 Physical height of an air-termination rod

h_2 $h_1 + H$, being the height of the air-termination rod over the ground

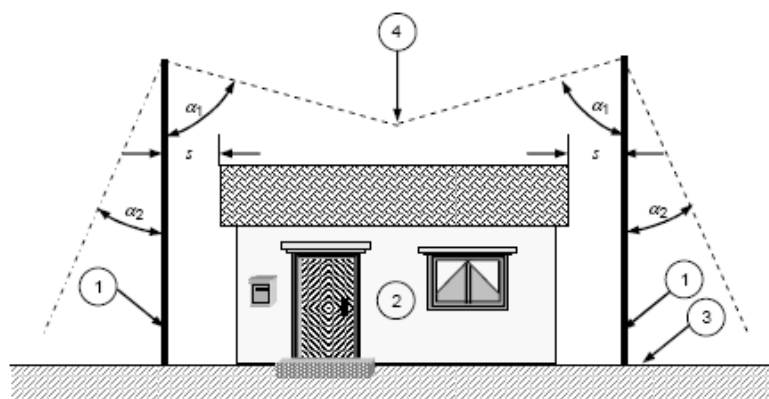
α_1 The protective angle corresponding to the air-termination height $h = h_1$, being the height above the roof surface to be measured (reference plane)

α_2 The protective angle corresponds to the height h_2

Fig. 28 Protective angle method air-termination design for different heights according to Table 5

The protective angle method has geometrical limits and cannot be applied if h is larger than the rolling sphere radius, r , as defined in Table 5. If structures on the roof are to be protected with finials and the protective volume of the finials is over the edge of the building, the finials should be placed between the structure and the edge. If this is not possible the rolling sphere method should be applied.

The design of air-termination using the protection angle air-termination design method is shown in Figures 29a and 29 b for an isolated LPS and in Figures 30a, 30b and 30c for a no isolated LPS.



Key

- 1 Air-termination mast
- 2 Protected structure
- 3 Ground being the reference plane
- 4 Intersection between protective cones
- s Separation distance
- α_1, α_2 Protective angle complying with Table 5

Fig. 29a) Projection on a vertical plane

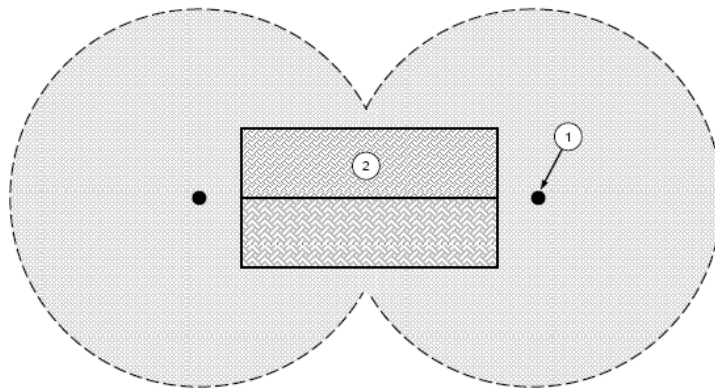


Fig. 29b) Projection on the horizontal reference plane

Fig. 29 Isolated external LPS using two isolated air-termination masts designed according to the protective angle air-termination design method

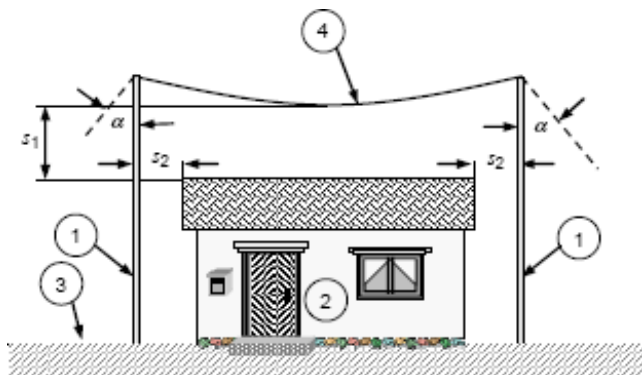


Fig. 30a) Projection on a vertical plane containing the two masts

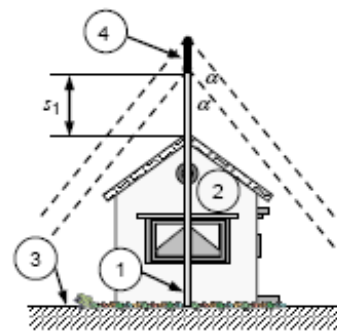
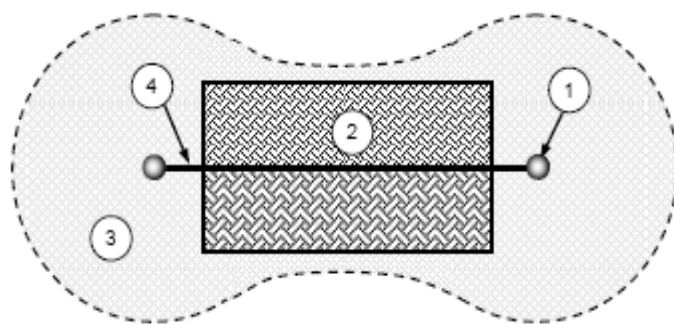


Fig. 30b) Projection on a vertical plane perpendicular to the plane containing the two mast

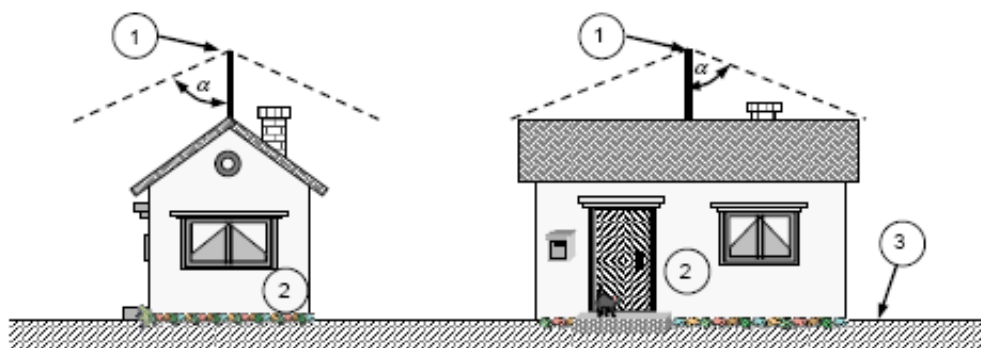


Key

- 1 Air-termination mast
- 2 Protected structure
- 3 Protected area on the reference plane
- 4 Horizontal wire air-termination
- s_1, s_2 Separation distances
- α Protective angle complying with Table 5

Fig. 30 c) Projection on the horizontal reference plane

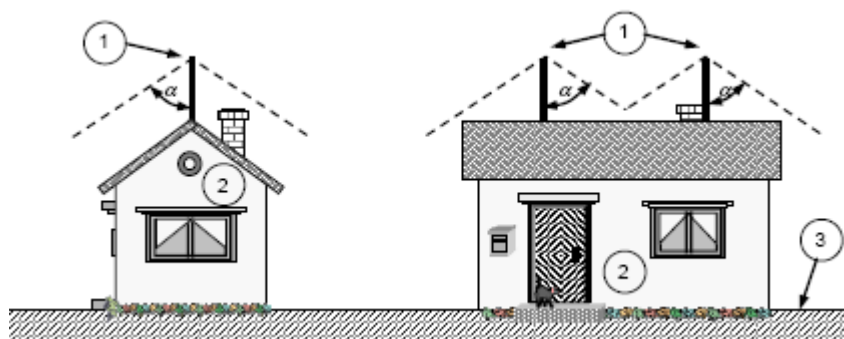
Fig.30 Isolated external LPS using two isolated air-termination masts, interconnected by horizontal catenary wire



Key

- 1 Air-termination rod
- 2 Protected structure
- 3 Assumed reference plane
- α Protective angle complying with Table 5

Fig. 31a) Example using one air-termination rod



Key

1 Air-termination rod

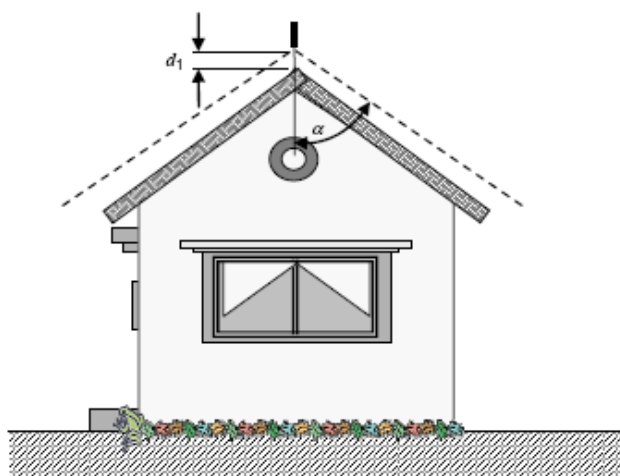
2 Protected structure

3 Assumed reference plane

α Protective angle complying with table 5

Fig. 31b) Example using two air-termination rods

Fig. 31 Example of design of an air-termination of a non-isolated LPS by air-termination rods



Key

α Protective angle complying with Table 5

d_1 Distance of horizontal wire from the roof

Fig.32 a) Projection on the vertical plane perpendicular to the plane containing the conductor



Key

α Protective angle complying with Table 5

Fig. 32b) Projection on a vertical plane containing the conductor

Fig. 32 Example of design of an air-termination of a non isolated LPS by a horizontal wire according to the protective angle air-termination design method

b) Positioning of the air-termination system utilizing the rolling sphere method

The rolling sphere method should be used to identify the protected space of parts and areas of a structure when Table 5 excludes the use of the protective angle method. Applying this method, the positioning of an air-termination system is adequate if no point of the volume to be protected is in contact with a sphere of radius, r , rolling on the ground, around and on top of the structure in all possible directions.

Therefore, the sphere should touch only the ground and/or the air-termination system.

The radius r of the rolling sphere depends on the class of LPS.

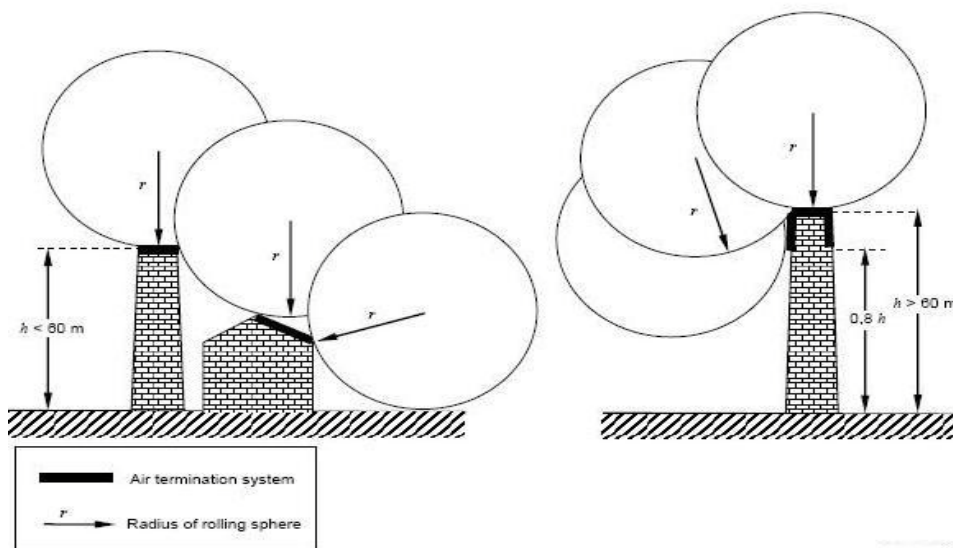
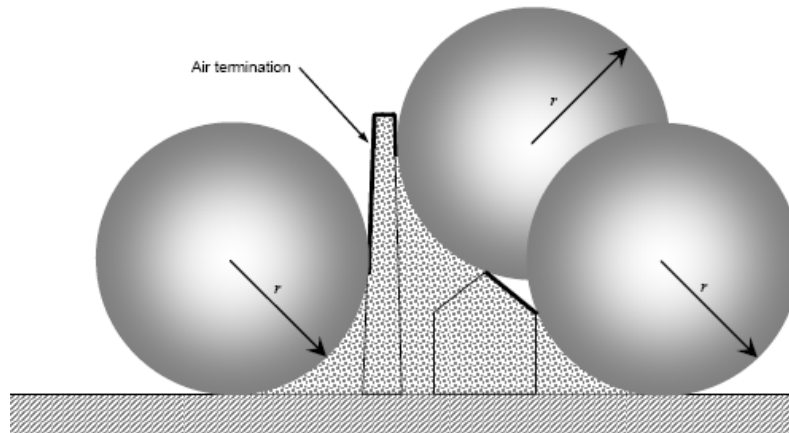


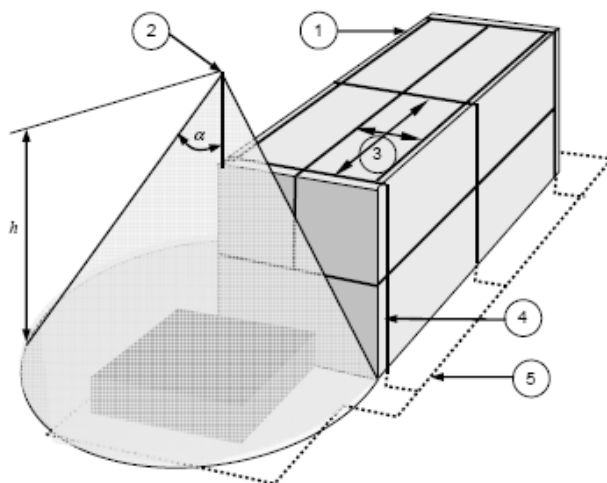
Fig. 33 Design of an air-termination system according to the rolling sphere method

On all structures higher than the rolling sphere radius r , flashes to the side of structure may occur. Each lateral point of the structure touched by the rolling sphere is a possible point of strike. However, the probability for flashes to the sides is generally negligible for structures lower than 60 m. For taller structures, the major part of all flashes will hit the top, horizontal leading edges and corners of the structure. Only a few per cent of all flashes will be to the side of the structure. Figures 12a) and 12b) show the application of the rolling sphere method to different structures. The sphere of radius r is rolled around and over all the structure until it meets the ground plane or any permanent structure or object in contact with the ground plane which is capable of acting as a conductor of lightning. A striking point could occur where the rolling sphere touches the structure and at such points protection by an air-termination conductor is required.



r Radius of the rolling sphere according to Table 5

Fig.34a) Design of an LPS air-termination according to the rolling sphere method



Key

- 1 Air-termination conductor
- 2 Air-termination rod
- 3 Mesh size
- 4 Down-conductor
- 5 Earthing system with ring conductor
- h Height of the air-terminal above ground level
- α Protective angle

Fig. 34b) Design of an LPS air-termination according to the rolling sphere method, protective angle method, mesh method and general arrangement of air-termination elements

c) Positioning of the air-termination system utilizing the mesh method

For the purposes of protecting flat surfaces, a mesh is considered to protect the whole surface, dependent upon all of the following conditions being fulfilled:

- Air-termination conductors are positioned
 - on roof edge lines,
 - on roof overhangs,
 - on roof ridge lines, if the slope of the roof exceeds 1/10.

The mesh dimensions of the air-termination network are not greater than the values given in Table 5.

- The network of the air-termination system is constructed in such a way that the lightning current will always encounter at least two distinct metal routes to earth termination.
- No metal installation protrudes outside the volume protected by air-termination systems.
- The air-termination conductors follow, as far as possible, the shortest and most direct route.

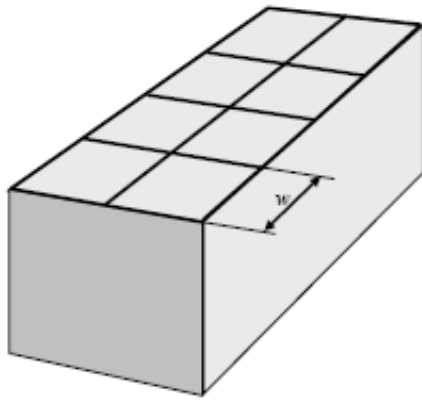


Fig. 35a) LPS air-termination on a flat-roof structure

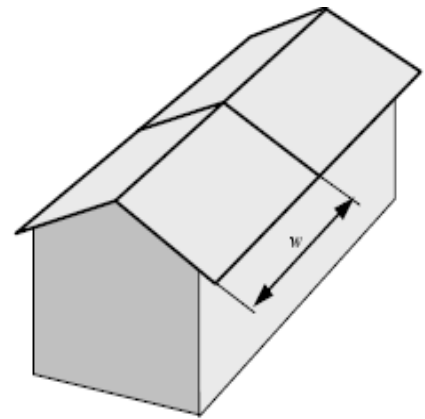


Fig. 35 b) LPS air-termination on a sloped- roof structure

w Mesh size

5.1.4 Construction

Air-terminations of an LPS not isolated from the structure to be protected may be installed as follows:

- if the roof is made of non-combustible material the air-termination conductors may be positioned on the surface of the roof;
- if the roof is made of readily-combustible material, due care needs to be taken with regard to the distance between the air-termination conductors and the material. For roofs where no steel bars are used for monitoring of the reed, a distance of 0,15m is adequate. For other combustible materials a distance not lower than 0,10m is considered adequate.
- Easily-combustible parts of the structure to be protected shall not remain in direct contact with the components of an external LPS and shall not remain directly under any metallic roofing membrane that might be punctured by a lightning flash.

5.1.5 Natural components

a) Metal sheets covering the structure to be protected provided that:

- the electrical continuity between the various parts is made durable (e.g. by means of brazing, welding, crimping, seaming, screwing or bolting);
- the thickness of the metal sheet is not less than the value t' given in Table 3 if it is not important to prevent puncture of the sheeting or to consider ignition of any readily-combustible materials underneath;
- the thickness of the metal sheet is not less than the value t given in Table 3 if it is necessary to take precautions against puncture or to consider hot spot problems;
- they are not clad with insulating material.

Class of LPS	Material	Thickness a t mm	Thickness b t' mm
I to IV	Lead	-	2,0
	Steel (stainless, galvanized)	4	0,5
	Titanium	4	0,5
	Copper	5	0,5
	Aluminium	7	0,65
	Zinc	-	0,7

t prevents puncture, hot spot or ignition.

t' only for metal sheets if it is not important to prevent puncture, hot spot or ignition problems.

Table 6 Minimum thickness of metal sheets or metal pipes in air-termination systems

- b) Metal components of roof construction (trusses, interconnected reinforcing steel, etc.), underneath non-metallic roofing, provided that this latter part can be excluded from the structure to be protected.
- c) Metal parts such as ornamentation, railings, pipes, coverings of parapets, etc., with cross-sections not less than that specified for standard air-termination components.
- d) Metal pipes and tanks on the roof, provided that they are constructed of material with thicknesses and cross-sections in accordance with Table 6.
- e) Metal pipes and tanks carrying readily-combustible or explosive mixtures, provided that they are constructed of material with thickness not less than the appropriate value of t given in Table 3 and that the temperature rise of the inner surface at the point of strike does not constitute a danger (for detailed information, see Annex E).

5.2 Down-conductor systems

5.2.1 General

Down-conductor system is part of an external LPS intended to conduct lightning current from the air-termination system to the earth-termination system. In order to reduce the probability of damage due to lightning current flowing in the LPS, the down-conductors shall be arranged in such a way that from the point of strike to earth:

- several parallel current paths exist;
- the length of the current paths is kept to a minimum;

-equipotential bonding to conducting parts of the structure is performed according to the requirements of IEC 62305

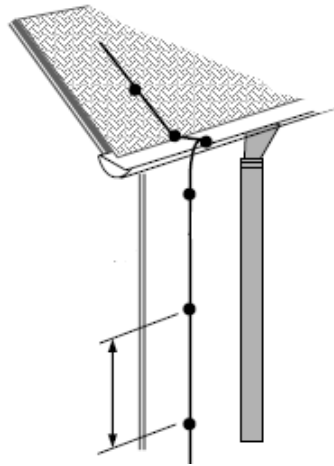


Fig.36 Installation of air-termination conductor on the ridge of a sloped roof and a roof down-conductor

5.2.2 Positioning

The down-conductors shall be installed so that, as far as practicable, they form a direct continuation of the air-termination conductors to the path to earth.

A down-conductor should be installed at each exposed corner of the structure, where this is possible.

Down-conductors should be placed as far as possible away from internal circuits and metallic parts in order to avoid the need for equipotential bonding with the LPS.

If it is not possible to place down-conductors at a side, or part of a side, of the building because of practical or architectural constraints, the down-conductors that ought to be on that side should be placed as extra compensating down-conductors at the other sides.

a) Positioning for an isolated LPS

- If the air-termination consists of rods on separate masts (or one mast) not made of metal or interconnected reinforcing steel, at least one down-conductor is needed for each mast. No additional down-conductors are required for masts made of metal or interconnected reinforcing steel.
- If the air-termination consists of catenary wires (or one wire), at least one down-conductor is needed at each supporting structure.
- If the air-termination forms a network of conductors, one down-conductor is needed at least at each supporting wire end.

b) Positioning for a non-isolated LPS

For each non-isolated LPS the number of down-conductors shall be not less than two and should be distributed around the perimeter of the structure to be protected.

Down-conductors of an LPS not isolated from the structure to be protected may be installed as follows:

- if the wall is made of non-combustible material, the down-conductors may be positioned on the surface or in the wall;

- if the wall is made of readily-combustible material the down-conductors may be positioned on the surface of the wall, provided that their temperature rise due to the passage of lightning current is not dangerous for the material of the wall;
- if the wall is made of readily-combustible material and the temperature rise of down-conductors is dangerous, the down-conductors shall be placed in such a way that the distance between them and the wall is always greater than 0,1 m. Mounting brackets may be in contact with the wall.

Typical values of the distance between down-conductors are given in Table 7.

Class of LPS	Typical distances m
I	10
II	10
III	15
IV	20

Table 7 Typical values of the distance between down-conductors and between ring conductors according to the class of LPS

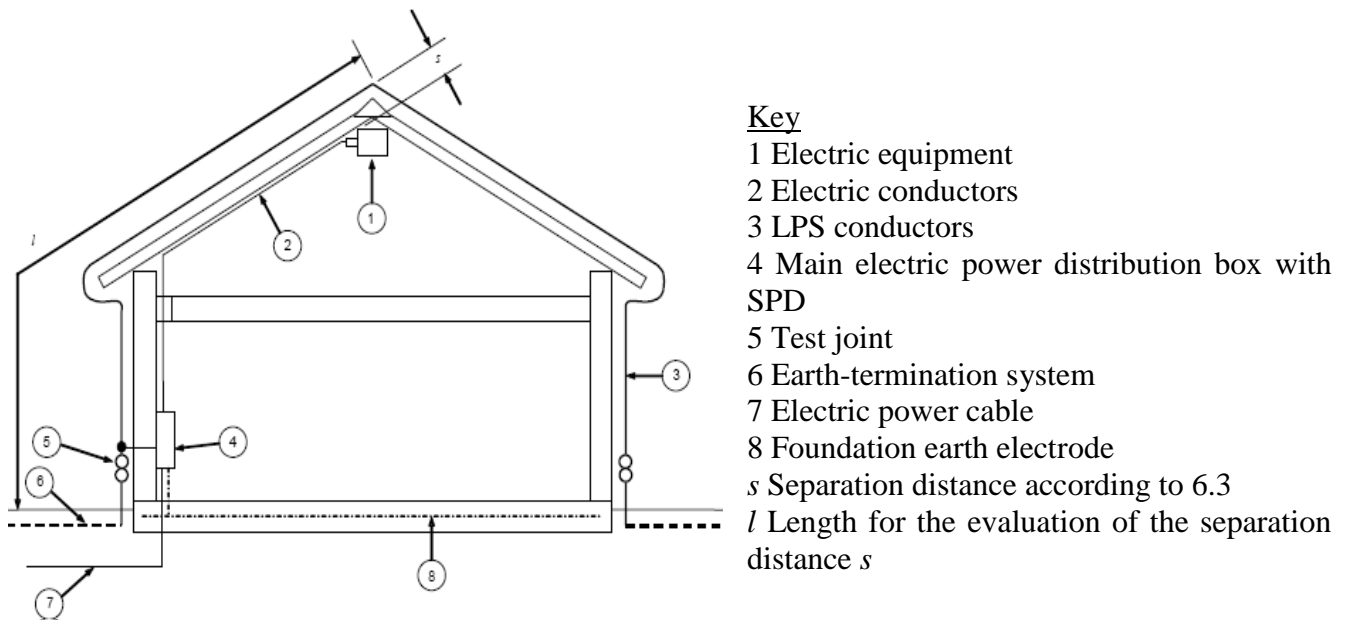
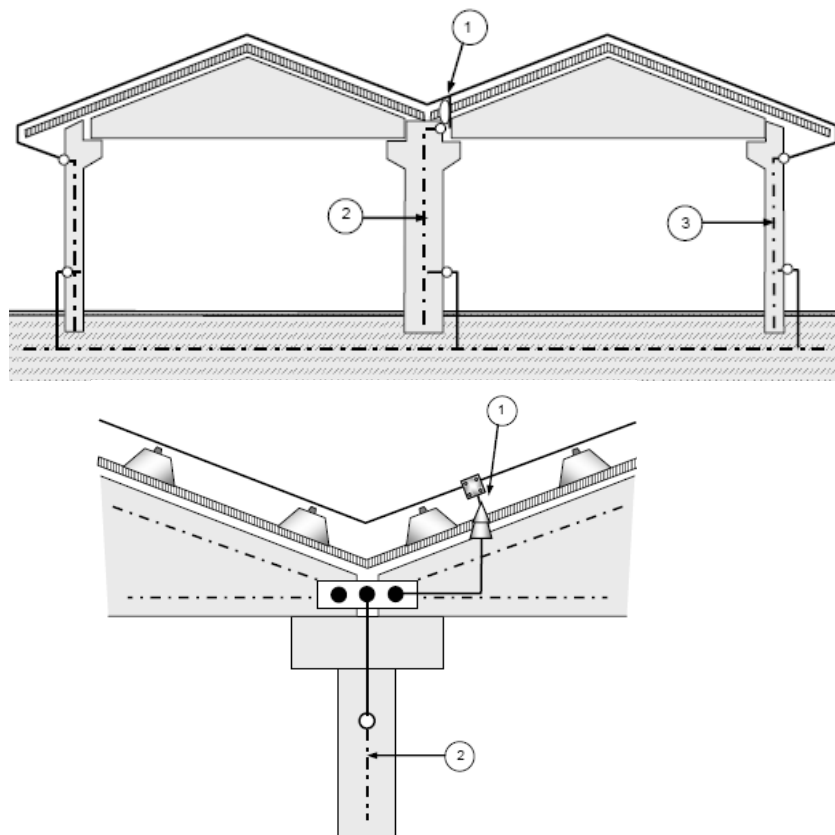


Fig. 37 Construction of an LPS using only two down-conductors and foundation earth electrodes



Key

- 1 LPS conductor passing a watertight bushing
- 2 Steel reinforcement in a concrete column
- 3 Steel reinforcement in concrete walls

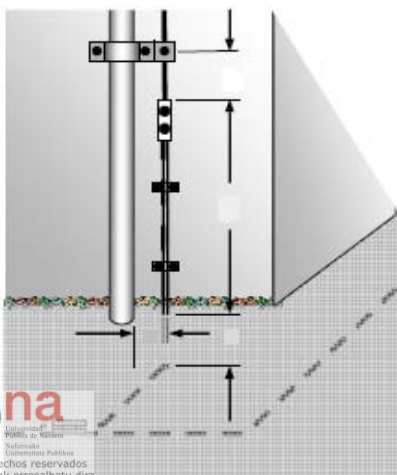
Fig. 38 Internal down-conductors in industrial structures

5.2.3 Natural components

The following parts of the structure should be considered as natural down-conductors:

- a) the metal installations
- b) the metal of the electrically-continuous reinforced concrete framework of the structure;
- c) the interconnected steel framework of the structure;
- d) the facade elements, profile rails and metallic sub-constructions of facades

5.2.4 Test joints

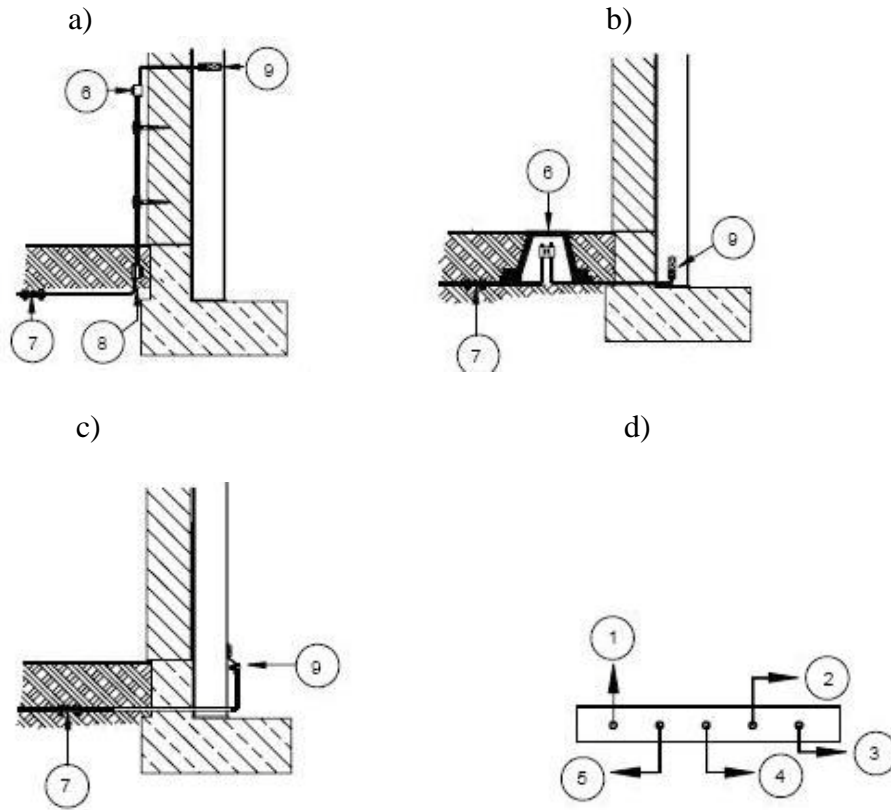


At the connection of the earth termination, a test joint should be fitted on each down-conductor, except in the case of natural down-conductors combined with foundation earth electrodes.

These joints facilitate the determination by measurement that an adequate number of connections to the earth-termination system still exists.

Fig. 39 Installation of a test joint in a down-conductor

Fig.40a through Fig. 40 d show examples of test joint designs, which may be installed on the inner or outer wall of a structure or in a test box in the earth outside the structure.



Alternative 1 – Test joint on wall

- 1 Down-conductor
- 2 Type B earth electrode, if applicable
- 3 Type A earth electrode, if applicable
- 4 Foundation earth electrode
- 5 Bonding to the internal LPS
- 6 Test joint on the wall
- 7 Corrosion-resistant T-joint in soil
- 8 Corrosion-resistant joint in soil
- 9 Joint between lightning conductor and a steel girder

Alternative 2 – Test joint in the floor

- 1 Down-conductor
- 2 Type A earth electrode, if applicable
- 3 Bonding bar of the internal LPS
- 4 Type B - Ring earth electrode
- 5 Type B - Ring earth electrode
- 6 Test joint in the floor
- 7 Corrosion-resistant T-joint in soil
- 8 Corrosion-resistant joint in soil
- 9 Joint between lightning conductor and a steel girder

Fig. 40 Examples of connection of earth termination to the LPS of structures using natural down-conductors (girders) and detail of a test joint

5.3 Earth-termination system

5.3.1 General

Earth-termination system is part of an external LPS which is intended to conduct and disperse lightning current into the earth.

Earth-termination systems should perform the following tasks:

- conduction of the lightning current into the earth;
- equipotential bonding between the down-conductors;
- potential control in the vicinity of conductive building walls.

When dealing with the dispersion of the lightning current (high frequency behaviour) into the ground, whilst minimizing any potentially dangerous overvoltages, the shape and dimensions of the earth-termination system are the important criteria. In general, a low earthing resistance is recommended.

5.3.2 Earthing arrangement in general conditions:

For earth-termination systems, two basic types of earth electrode arrangements apply:

- **Type A arrangement**

This type of arrangement comprises horizontal or vertical earth electrodes installed outside the structure to be protected connected to each down-conductor.

In type A arrangements, the total number of earth electrodes shall be not less than two.

The minimum length of each earth electrode at the base of each down-conductor is

l_1 for horizontal electrodes, or

$0,5 l_1$ for vertical (or inclined) electrodes, where

l_1 is the minimum length of horizontal electrodes shown in the relevant part of Fig. 41.

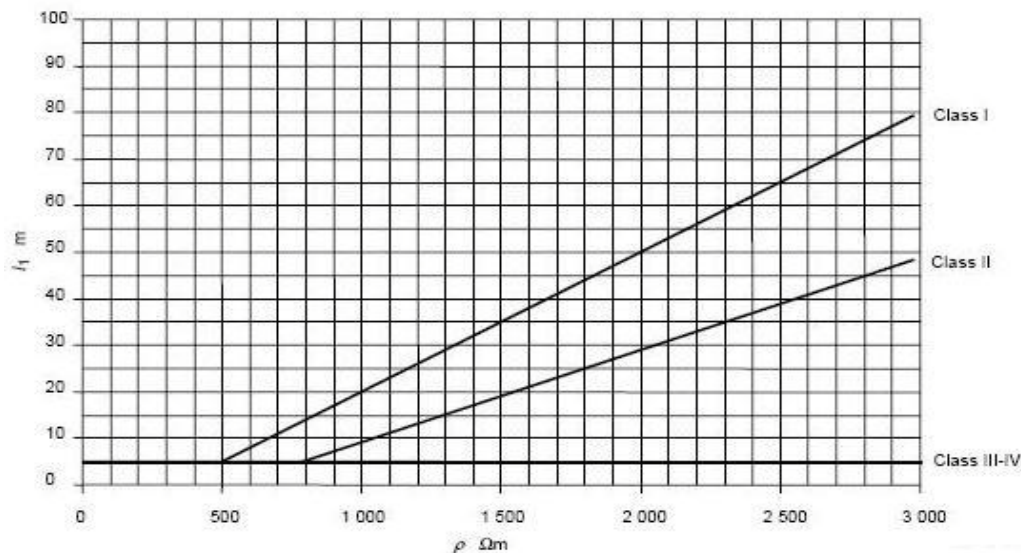


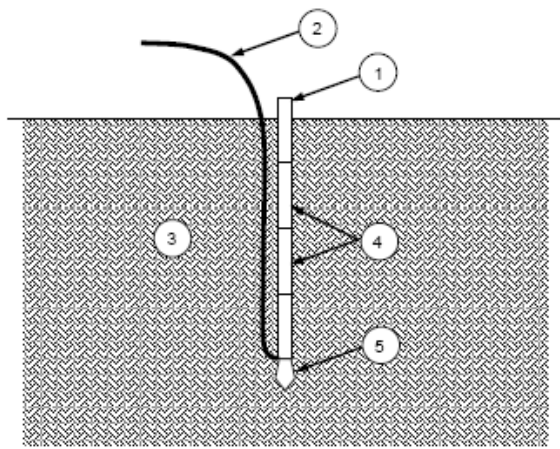
Fig. 41 Minimum length l_1 of each earth electrode according to the class of LPS

NOTE Classes III and IV are independent of soil resistivity.

For combined (vertical or horizontal) electrodes, the total length shall be considered. The type A earth-termination system is suitable for low structures (for example family houses), existing structures or an LPS with rods or stretched wires or for an isolated LPS.

Where there is a ring conductor, which interconnects the down-conductors, in contact with the soil the earth electrode arrangement is still classified as type A if the ring conductor is in contact with the soil for less than 80 % of its length.

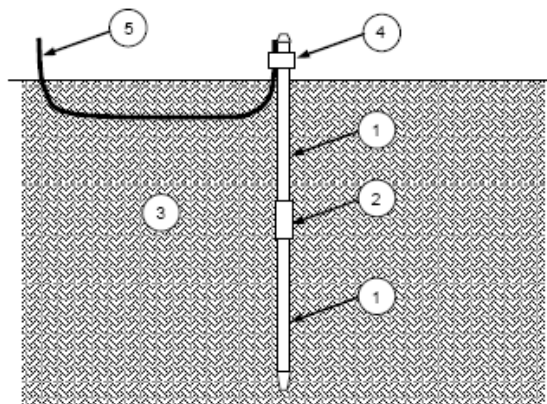
Figure 42 shows a type A earth electrode where a lightning conductor in accordance with is pushed into the soil using special driving rods.



Key

- 1 Short upper-most driving rod
- 2 Earthing conductor
- 3 Soil
- 4 Short driving rods
- 5 Driving steel dart

Fig. 42a) Example of a type A earthing arrangement with a vertical conductor type electrode



Key

- 1 Extensible earth rod
- 2 Rod coupling
- 3 Soil
- 4 Conductor to rod clamp
- 5 Earthing conductor

Fig.42b) Example of a type A earthing arrangement with a vertical rod type electrode

• Type B arrangement

Ring earthing electrode

earthing electrode forming a closed loop around the structure below or on the surface of the earth.

Foundation earthing electrode

reinforcing steel of foundation or additional conductor embedded in the concrete foundation of a structure and used as an earthing electrode.

This type of arrangement comprises either a ring conductor external to the structure to be protected, in contact with the soil for at least 80 % of its total length, or a foundation earth electrode. Such earth electrodes may also be meshed.

For the ring earth electrode (or foundation earth electrode), the mean radius r_e of the area enclosed by the ring earth electrode (or foundation earth electrode) shall be not less than the value l_1 :

$$r_e > l_1$$

where l_1 is represented in Figure 5 according to LPS class I, II, III and IV.

When the required value of l_1 is larger than the convenient value of r_e , additional horizontal or vertical (or inclined) electrodes shall be added with individual lengths l_r (horizontal) and l_v (vertical) given by the following equations:

$$l_r = l_1 - r_e$$

$$l_v = (l_1 - r_e)/2$$

It is recommended that the number of electrodes shall be not less than the number of the down-conductors, with a minimum of two.

The additional electrodes should be connected to the ring earth electrode at points where the down-conductors are connected and, for as many as possible, equidistantly.

The type B earth-termination system is preferred for meshed air-termination systems and for LPS with several down-conductors.

5.3.3 Installation of earth electrodes

The LPS designer and the LPS installer should select suitable types of earth electrodes and should locate them at safe distances from entrances and exits of a structure and from the external conductive parts in the soil. The LPS designer and the LPS installer should make special provisions for protection against dangerous step voltages in the vicinity of the earth-termination networks if they are installed in areas accessible to the public.

The ring earth electrode (type B arrangement) should preferably be buried at a depth of at least 0,5 m and at a distance of about 1 m around the external walls.

The earth electrodes (type A arrangement) shall be installed at a depth of upper end at least 0,5 m and distributed as uniformly as possible to minimize electrical coupling effects in the earth.

Earth electrodes shall be installed in such a way as to allow inspection during construction.

For structures with extensive electronic systems or with high risk of fire, type B earthing arrangement is preferable.

5.3.4 Foundation earth electrodes

A foundation earth electrode comprises conductors, which are installed in the foundation of the structure below ground. The length of additional earth electrodes should be determined using the diagram in Figure 5.

Foundation earth electrodes are installed in concrete. They have the advantage that, if the concrete is of adequate construction and covers the foundation earth electrode by at least 50 mm, they are reasonably protected against corrosion. It should also be remembered that reinforcing steel rods in concrete generate the same magnitude of galvanic potential as copper conductors in soil. This offers a good engineering solution to the design of earth-termination systems for reinforced concrete structures.

Earth electrodes in soil should use copper or stainless steel conductors where these are connected to steel in concrete.

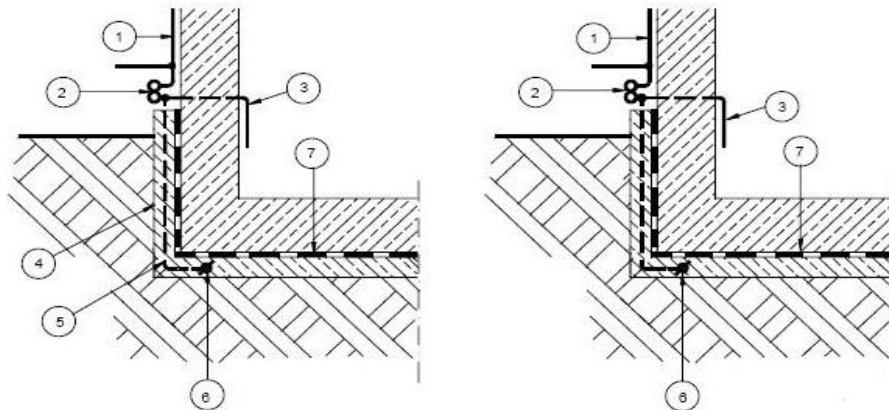
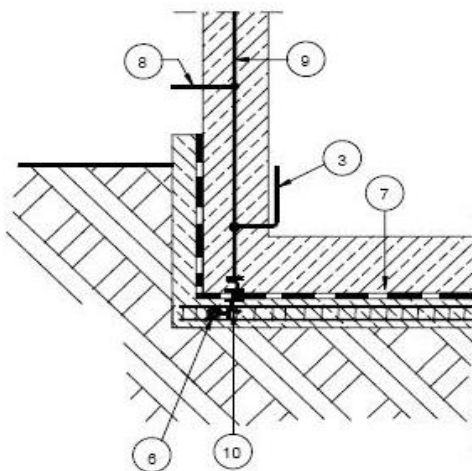


Fig.43 a) Isolated foundation with foundation earth electrode in the non-reinforced concrete layer below the bitumen insulation Fig.43 b) Isolated foundation with earth- termination conductor partly passing through the soil



Key

- 1 Down-conductor
- 2 Test joint
- 3 Bonding conductor to the internal LPS
- 4 Non-reinforced layer of concrete
- 5 Connecting conductor of the LPS
- 6 Foundation earth electrode
- 7 Bitumen insulation, watertight insulating layer
- 8 Connecting conductor between steel reinforcement and the test joint
- 9 Steel reinforcement in concrete
- 10 Puncturing of the watertight bitumen lay

Fig. 43 c) Connecting conductor from the foundation earth electrode to the bonding bar passing the between insulating layer

Fig.43 Construction of foundation earth ring for structures of different foundation design

❖ Internal lightning protection system

1. General

Internal lightning protection system is part of the LPS consisting of:

- lightning equipotential bonding
- electrical insulation of external LPS.

The external lightning protection system and its relationship to conductive parts and installations inside the structure will determine, to a large extent, the need for an internal lightning protection system.

The internal lightning protection is the same for all protection levels except for the separation distances.

2. Structure

2.1 Lightning equipotential bonding

Lightning equipotential bonding is bonding to the LPS of separated conductive parts, by direct connections or via surge protective devices, to reduce potential differences caused by lightning current.

2.1.1 General

Equipotentialization is achieved by interconnecting the LPS with

- structural metal parts,
- metal installations,
- internal systems,
- external conductive parts and lines connected to the structure.

When lightning equipotential bonding is established to internal systems, part of the lightning current may flow into such systems and this effect shall be taken into account.

2.1.2 Design

Interconnecting means can be bonding conductors, where the electrical continuity is not provided by natural bonding, and surge protective devices (SPDs), where direct connections with bonding conductors is not feasible.

- **Bonding conductors**

Bonding conductors should be able to withstand the part of the lightning current flowing through them. Conductors bonding metal installations internal to the structure normally do not carry a significant part of the lightning current. Conductors bonding external conductive parts to the LPS usually carry a substantial part of the lightning current.

- **Surge protective devices**

Surge protective devices (SPDs) should withstand the prospective part of the lightning current flowing through them without being damaged. An SPD should also have the ability to extinguish electrical power follow-on currents from the power supply if they are connected to the electrical power conductors.

2.1.3 Kind of lightning equipotential bonding

- **Lightning equipotential bonding for metal installations**

In the case of an isolated external LPS, lightning equipotential bonding shall be established at ground level only.

For an external LPS which is not isolated, lightning equipotential bonding shall be installed at the following locations:

- in the basement or approximately at ground level.

Bonding conductors shall be connected to a bonding bar constructed and installed in such a way that it allows easy access for inspection. The bonding bar shall be connected to the earth-termination system. For large structures (typically more than 20 m in length), more than one bonding bar can be installed, provided that they are interconnected;

- where insulation requirements are not fulfilled

Lightning equipotential bonding connections shall be made as direct and straight as possible. The minimum values of the cross-section of the bonding conductors connecting different bonding bars and of the conductors connecting the bars to the earth-termination system are listed in Table 8.

Class of LPS	Material	Cross-section mm ²
I to IV	Copper	14
	Aluminium	22
	Steel	50

Table 8 Minimum dimensions of conductors connecting different bonding bars or connecting bonding bars to the earth-termination system

The minimum values of the cross-section of the bonding conductors connecting internal metal installations to the bonding bars are listed in Table 9.

Class of LPS	Material	Cross-section mm ²
I to IV	Copper	5
	Aluminium	8
	Steel	16

Table 9 Minimum dimensions of conductors connecting internal metal installations to the bonding bar

If insulating pieces are inserted into gas lines or water pipes, inside the structure to be protected they shall, with the agreement of the water and gas supplier, be bridged by SPDs designed for such an operation.

SPDs shall have the following characteristics:

- class I test;
- $I_{imp} \geq k_c I$ with $k_c I$ being the lightning current flowing along the relevant part of the external LPS
- the protection level UP shall be lower than the impulse withstand level of insulation between parts;
- other characteristics conforming to IEC 61643-12.

- **Lightning equipotential bonding for external conductive parts**

For external conductive parts, lightning equipotential bonding shall be established as near as possible to the point of entry into the structure to be protected.

Bonding conductors shall be capable of withstanding the part I_f of the lightning current flowing through them evaluated in accordance with Annex E of IEC 62305-1.

If direct bonding is not acceptable, SPDs with the following characteristics shall be used:

- class I test;
- $I_{imp} \geq I_f$ with I_f being the lightning current flowing along the considered external conductive part (see Annex E of IEC 62305-1);
- the protection level UP shall be lower than the impulse withstand level of insulation between parts;
- other characteristics conforming to IEC 61643-12.

- **Lightning equipotential bonding for internal systems**

If the internal systems conductors are screened or located in metal conduits, it may be sufficient to bond only these screens and conduits.

If conductors of internal systems are neither screened nor located in metal conduits, they shall be bonded via SPDs.

All the conductors of each line should be bonded directly or with an SPD. Live conductors shall only be bonded to the bonding bar via an SPD. In TN systems, PE and PEN conductors shall be bonded to the LPS directly or with a SPD.

Bonding conductors and SPDs shall have the same characteristics as indicated in first case.

- **Equipotential bonding of internal conductive parts**

Bonding should be provided and installed in such a way that the internal conductive parts, the external conductive parts and the electrical power and communication systems (for example computers and security systems) can be bonded by short bonding conductors, and where necessary utilizing SPDs.

Metal installations, i.e. water, gas, heating and air pipes, lift shafts, crane supports etc. shall be bonded together and to the LPS at ground level.

Sparkling can occur in metal parts not belonging to the structure if those parts are close to the down-conductors of the LPS. Where this is considered dangerous, adequate bonding measures should be used to prevent sparking.

A bonding bar arrangement is shown in Figure E.45

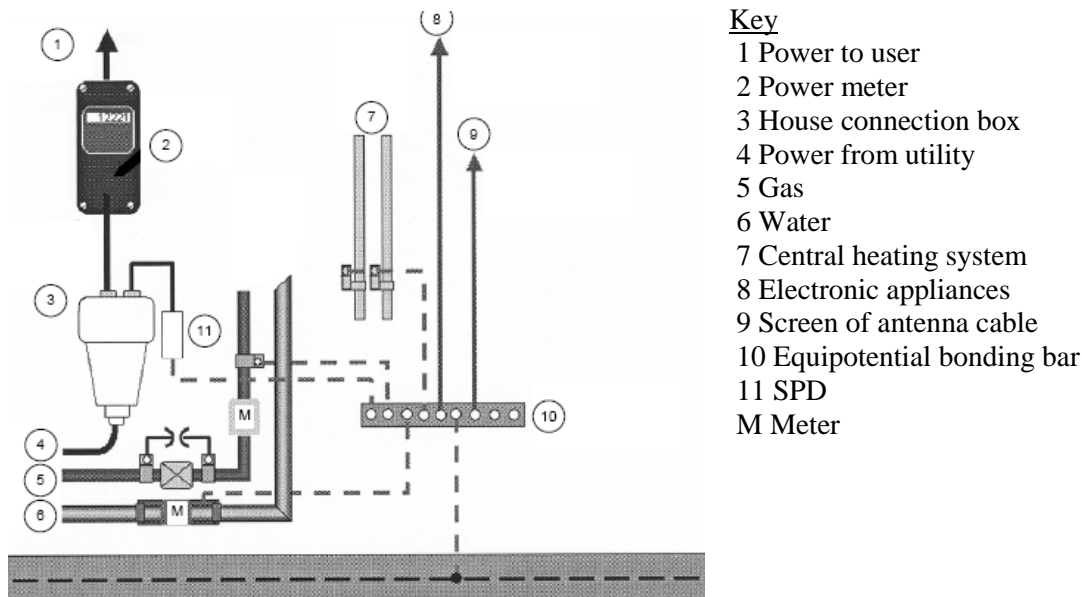


Fig.44 Example of an equipotential bonding arrangement

The bonding bars should be located so that they are connected to the earth-termination system or to the horizontal ring conductors with short conductors.

The bonding bar is preferably installed at the inner side of an outer wall near ground level, close to the main low-voltage power distribution box and closely connected to the earth termination system comprising the ring earth electrode, the foundation earth electrode and the natural earth electrode such as the interconnected reinforcing steel, where applicable.

2.2 Electrical insulation of the external LPS

An adequate separation distance, should be maintained between the external LPS and all conductive parts connected to the equipotential bonding of the structure.

The electrical insulation between the air-termination or the down-conductor and the structural metal parts, the metal installations and the internal systems can be achieved by providing a distance d between the parts greater than the separation distance s :

where $s = k_i \cdot (k_c / k_m) \cdot l$

k_i depends on the selected class of LPS

k_c depends on the lightning current flowing on the down-conductors

k_m depends on the electrical insulation material

l is the length, in metres, along the air-termination or the down-conductor, from the point where the separation distance is to be considered, to the nearest equipotential bonding point.

Class of LPS	k_1
I	0,08
II	0,06
III and IV	0,04

Table 8 Isolation of external LPS – Values of coefficient k_1

Number of down-conductors n	Detailed values (see Table C.1) k_0
1	1
2	1 ... 0,5
4 and more	1 ... 1/ n

Table 9 Isolation of external LPS – Values of coefficient k_0

Material	k_m
Air	1
Concrete, bricks	0,5
NOTE 1 When there are several insulating materials in series, it is good practice to use the lower value for k_m .	
NOTE 2 The use of other insulating materials is under consideration.	

Table 10 Isolation of external LPS – Values of coefficient k_m

The reference length l for the calculation of the separation distance s , should be the distance between the connection point to the equipotential bonding and the point of proximity along the down-conductor. The roof and down-conductors should follow a route as straight as possible to keep the necessary separation distance low. The length and the path of the conductor within the building running from bonding bar to point of proximity is generally of little influence on the separation distance, but when this conductor runs close to a lightning current-carrying conductor the necessary separation distance will be lower.

Figure 45a) and Figure 45b) illustrate how the critical length l used for calculation of the separation distance s , is measured on an LPS.

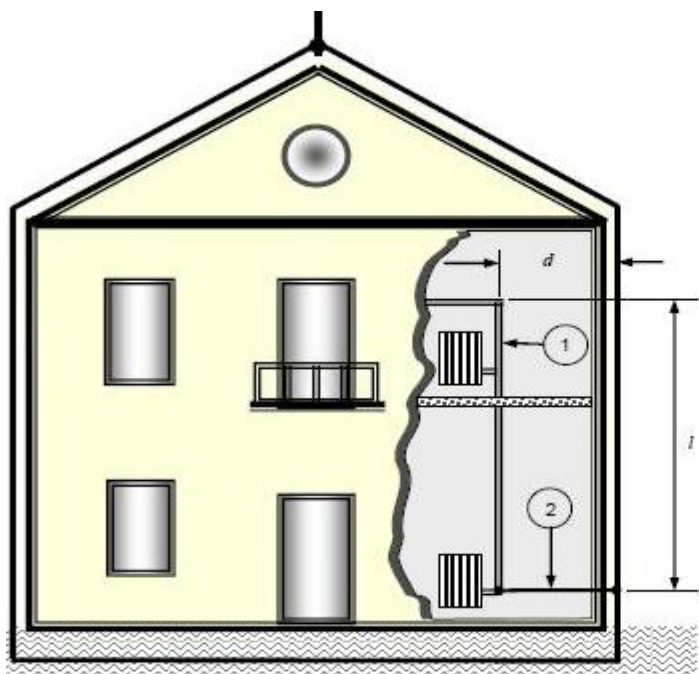


Fig.45a) Calculated separation
distance $s < d$

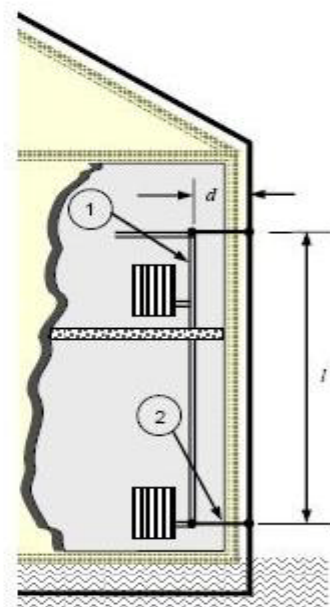


Fig.45b) Calculated separation
distance $s > d$

Key

1 Metal pipe

2 Equipotential bonding

d Distance between a down-conductor and a metallic installation inside the building

l Length for the evaluation of separation distance s

s Separation distance

Fig.45 Examples of separation distance between the LPS and metal installations

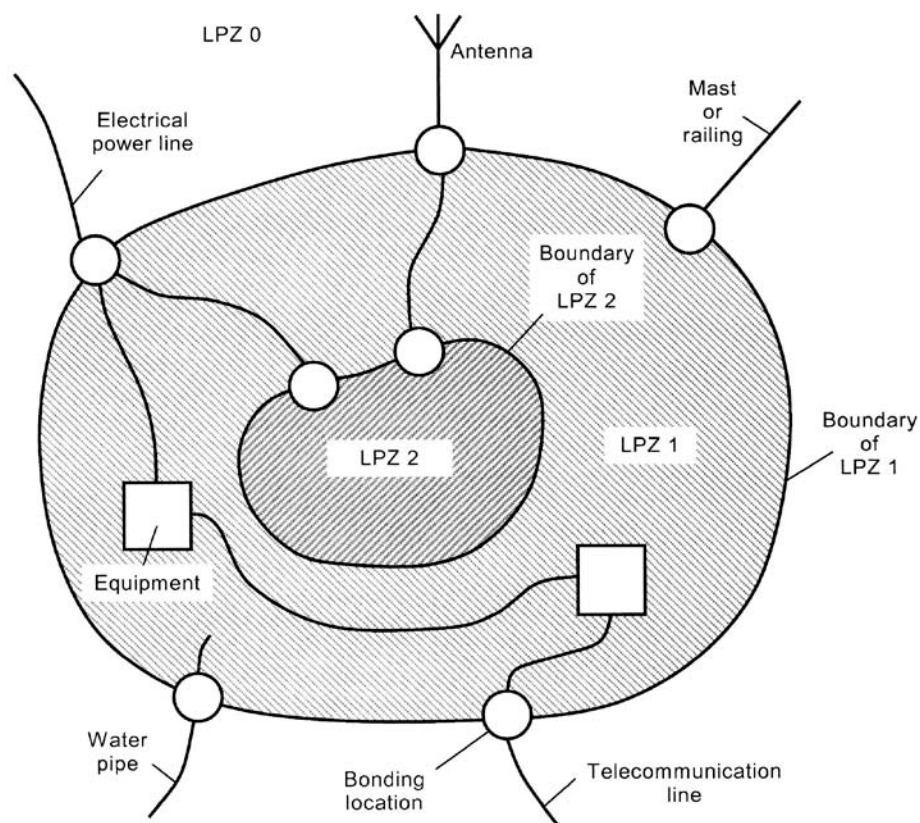
3. LEMP protection measures system (LPMS)

LPMS is complete system of protection measures for internal systems against LEMP.

3.1 Lightning protection zone (LPZ)

The protection of the systems against surges is based on the principle of lightning protection zones (LPZ), in which the building or structure being protected is divided according to the level of threat. Using this approach, suitable zones can be defined according to the number, type and sensitivity of the electronic devices or systems, ranging from small local zones to large integral zones that can encompass the whole building. The requirements for the internal zones need to be defined according to the immunity of the electrical and electronic systems to be protected.

Protection against LEMP is based on the lightning protection zone (LPZ) concept (IEC Standard 62305-4): the volume containing systems to be protected shall be divided into LPZ. These zones are theoretically assigned volumes of space where the LEMP severity is compatible with the withstand level of the internal systems enclosed (see Figure 46). Successive zones are characterized by significant changes in the LEMP severity.



O Bonding of incoming services directly or by suitable

NOTE This figure shows an example for dividing a structure into inner LPZs. All metal services entering the structure are bonded via bonding bars at the boundary of LPZ 1. In addition, the conductive services entering LPZ 2 (e.g. computer room) are bonded via bonding bars at the boundary of LPZ 2.

Fig. 46 General principle for the division into different LPZ (IEC 62305-4)

With respect to lightning threat, the following LPZ are defined.

Outer Zones:

LPZ 0 zone where the threat is due to the unattenuated lightning electromagnetic field and where the internal systems may be subjected to full or partial lightning surge currents. LPZ 0 is divided into:

LPZ 0A zone where the threat is due to the direct lightning flash and the full lightning electromagnetic field. The internal systems may be subjected to full lightning surge currents (10/350 μ s wave shape)

LPZ 0B zone protected against direct lightning flashes but where the threat is the full lightning electromagnetic field. The internal systems may be subjected to partial lightning surge currents. (In 8/20 μ s wave shape)

Inner Zones: (protection against direct lightning flashes):

LPZ 1 Zone where the surge current is limited by current sharing and by SPDs at the boundary. Spatial shielding may attenuate the lightning electromagnetic field.

LPZ 2....n Zone where the surge current may be further limited by current sharing and by additional SPDs at the boundary. Additional spatial shielding may be used to further attenuate the lightning electromagnetic field.

Lightning Protection Zones Concept described in IEC 62305-4 is applied (Fig. 5). A structure is subdivided in different risk zones. With these zones the necessary devices and components can be defined for the lightning and surge protection.

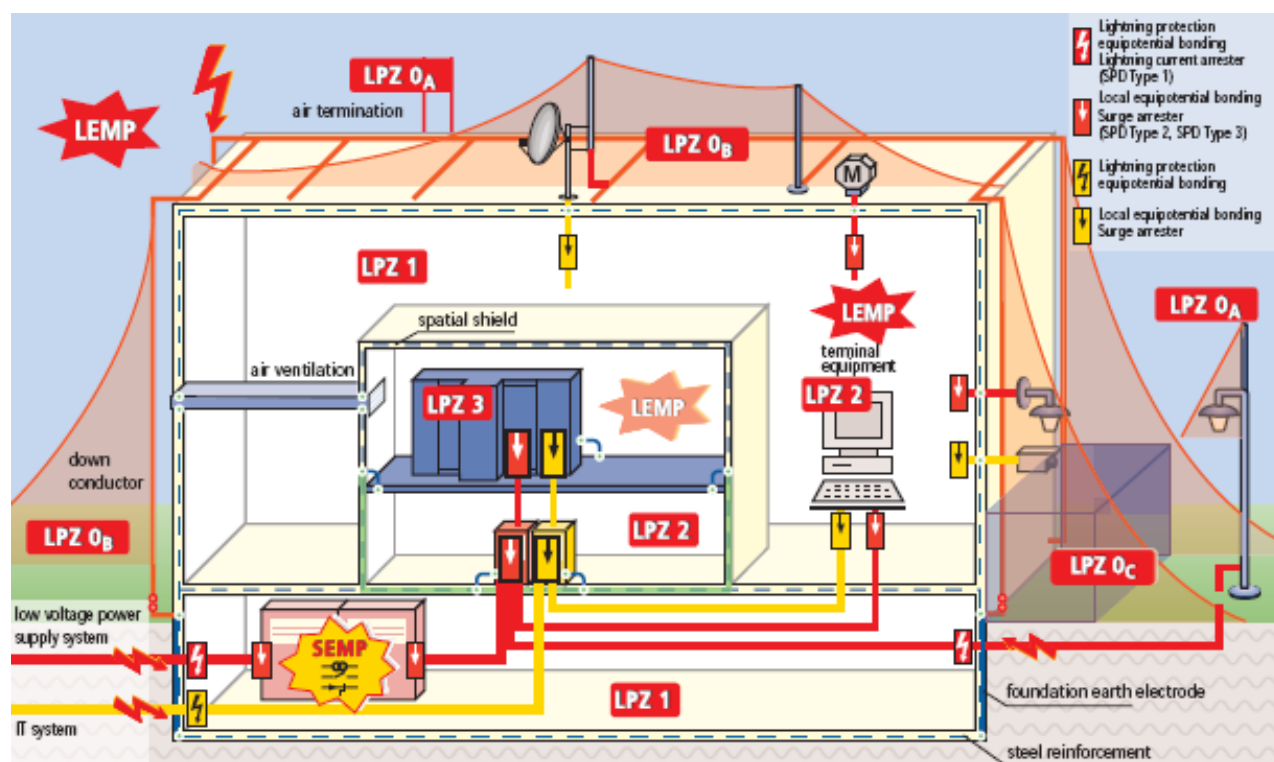


Fig.47 Lightning protection zones concept

Transition from LPZ 0A to LPZ 1:

- Services between LPZ 0A and LPZ 1 carry substantial lightning
- At the interface between LPZ 0A and LPZ 1, Class I lightning current SPDs are required

Transition from LPZ 0B to LPZ 1:

- In LPZ 0B, electromagnetic fields caused by lightning currents are dominant. A direct stroke is excluded

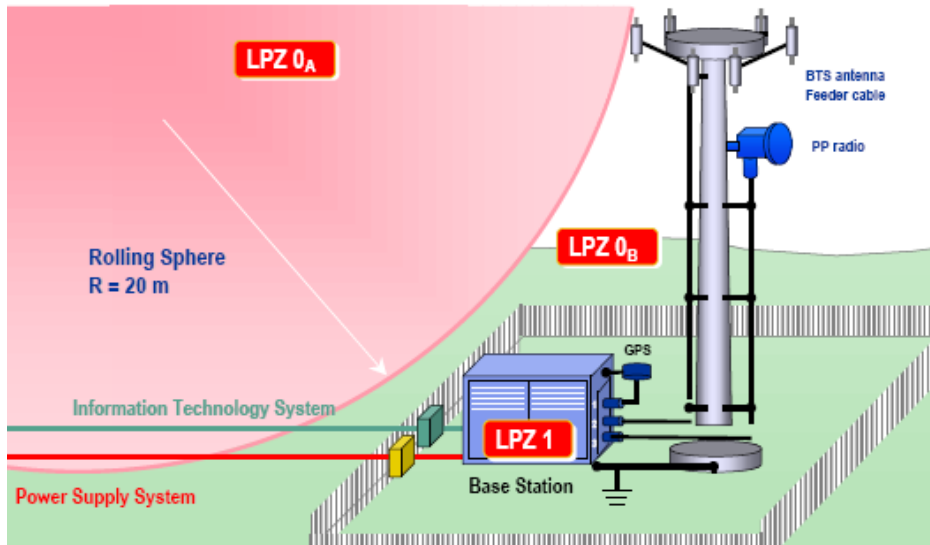


Fig.48 Lightning Protection Zone Concept

- In 99% of all cases conducting services traverse from LPZ 0A through LPZ 0B to get to LPZ 1
- In very few cases will conducting services only traverse from LPZ 0B to LPZ 1

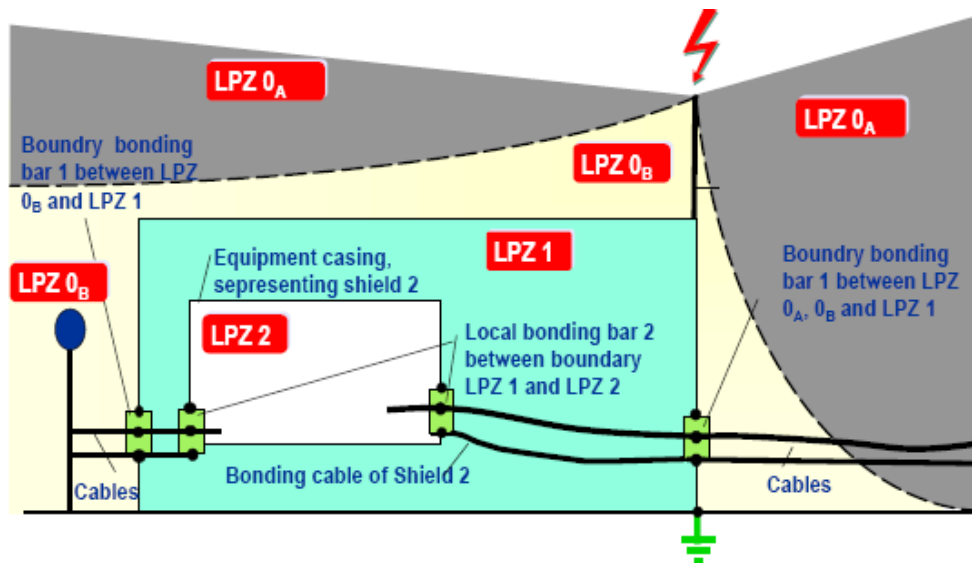


Fig.49 Transition from LPZ 0B to LPZ 1

Electrical and electronic systems are subject to damage from the lightning electromagnetic impulse (LEMP). Therefore LEMP protection measures need to be provided to avoid failure of internal systems.

Figure 50 provides an example of the LEMP in the case of lightning flash to the structure showing the lightning protection zones LPZ 0, LPZ 1 and LPZ 2. The electronic system to be protected is installed inside LPZ 2.

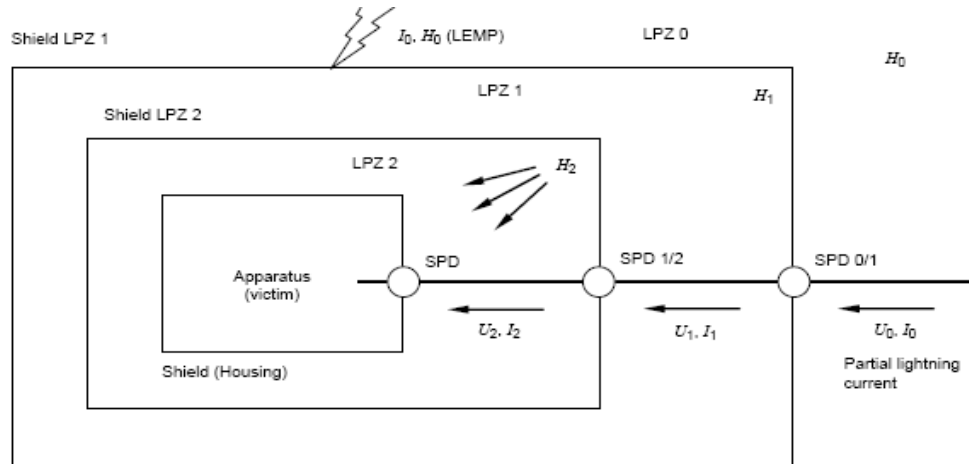
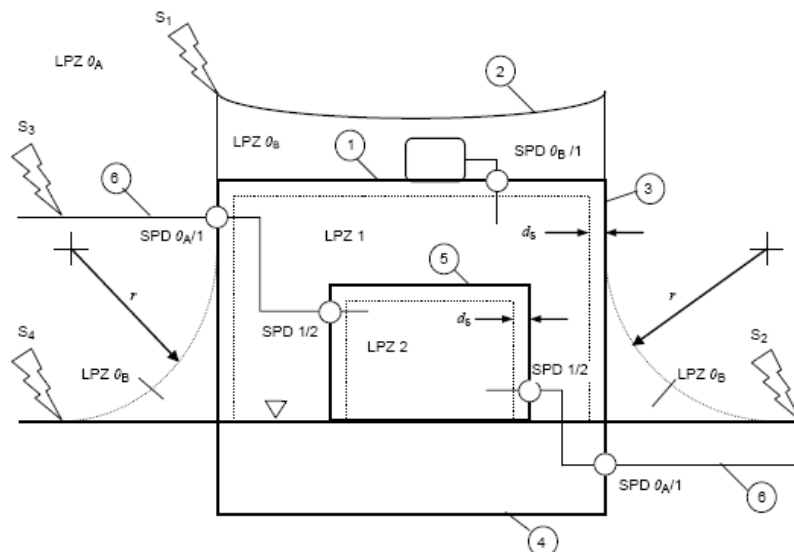


Fig. 50 LEMP situation due to lightning flash

The primary electromagnetic source of harm to the electronic system is the lightning current I_0 and the magnetic field H_0 . Partial lightning currents flow on the incoming services. These currents as well as the magnetic fields have the same waveshape. The lightning current to be considered here consists of a first stroke I_f (typically with a long tail 10/350 μ s waveshape) and subsequent strokes I_s (0,25/100 μ s waveshape). The current of the first stroke I_f generates the magnetic field H_f and the currents of the subsequent strokes I_s generate the magnetic fields H_s .



1	Structure (shield of LPZ 1)	S1	Flash to the structure
2	Air termination system	S2	Flash near to the structure
3	Down conductor system	S3	Flash to a service connected to the structure
4	Earth termination system	S4	Flash near a service connected to the structure
5	Room (shield of LPZ 2)	r	Rolling sphere radius
6	Services connected to the structure	d_s	Safety distance against too high magnetic field

▽ Ground level

○ Lightning equipotential bonding by means SPD

LPZ 0_A Direct flash, full lightning current, full magnetic field

LPZ 0_B No direct flash, partial lightning or induced current, full magnetic field

LPZ 1 No direct flash, limited lightning or induced current, damped magnetic field

LPZ 2 No direct flash, induced currents, further damped magnetic field

Protected volumes inside LPZ 1 and LPZ 2 must respect safety distances d_s

Fig.51 LPZ defined by protection measures against LEMP (IEC 62305-4)

Interconnection of LPZ of the same order may be necessary if either two separate structures are connected by electrical or signal lines, or the number of required SPDs is to be reduced(see Figure52).

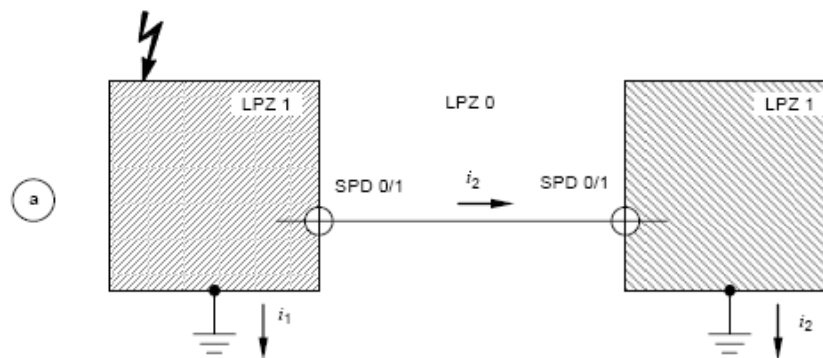


Fig. 52 a) Interconnecting two LPZ 1 using SPD

NOTE Figure 52 a) shows two LPZ1 connected by electrical or signal lines. Special care should be taken if both LPZ1 represent separate structures with separate earthing systems, spaced tens or hundreds of meters from each other. In this case, a large part of the lightning current can flow along the connecting lines, which are not protected.

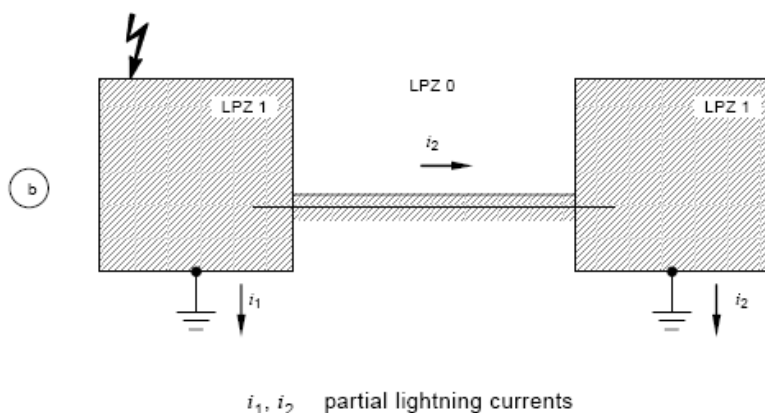


Fig.52 b) Interconnecting two LPZ 1 using shielded cables or shielded cable ducts

NOTE Figure 52b) shows, that this problem can be solved using shielded cables or shielded cable ducts to interconnect both LPZ 1, provided that the shields are able to carry the partial lightning current. The SPD can be omitted, if the voltage drop along the shield is not too high

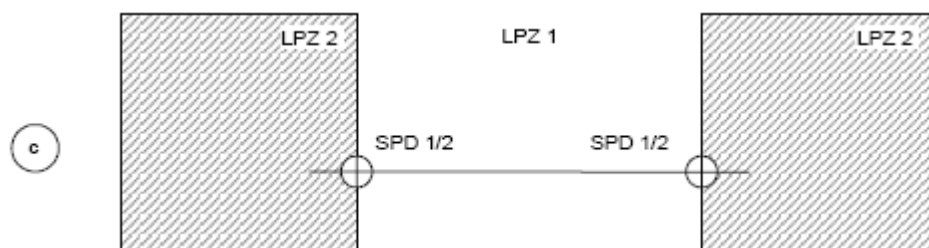


Fig. 52c) Interconnecting two LPZ 2 using SPD

NOTE Figure 52c) shows two LPZ 2 connected by electrical or signal lines. Because the lines are exposed to the threat level of LPZ 1, SPD at the entry into each LPZ 2 are required.

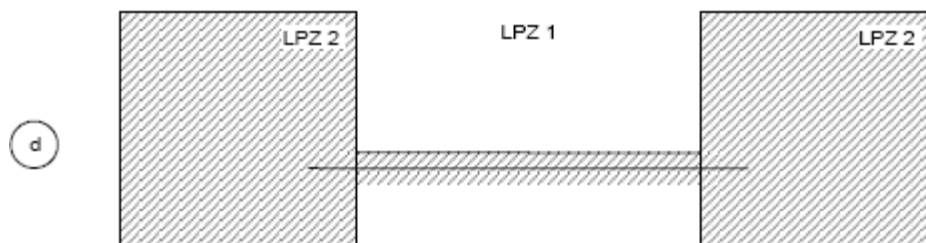


Fig.52d) Interconnecting two LPZ 2 using shielded cables or shielded cable ducts

NOTE Figure 52d) shows that such interference can be avoided and the SPD can be omitted, if shielded cables or shielded cable ducts are used to interconnect both LPZ 2.

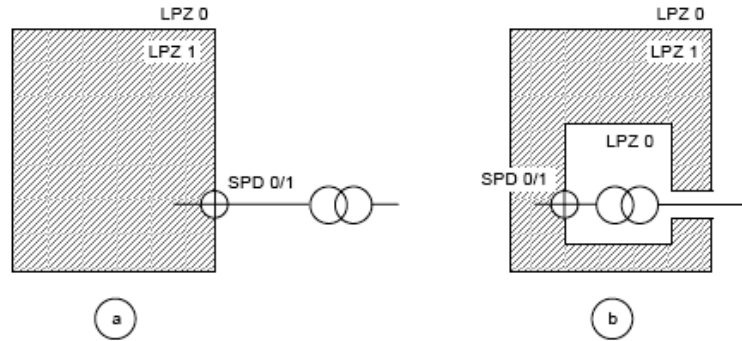


Fig. 53a) Transformer outside the structure

NOTE Figure 53a) shows a structure powered by a transformer. If the transformer is placed outside the structure, only the low voltage lines entering the structure need protection by SPD. If the transformer should be placed inside the structure, the owner of the building often is not allowed to adopt protection measures on the high voltage side.

Fig.53b) Transformer inside the structure (LPZ 0 extended into LPZ 1)

NOTE Figure 53b) shows that the problem can be solved extending LPZ 0 into LPZ 1, which requires again SPDs at the low voltage side only.

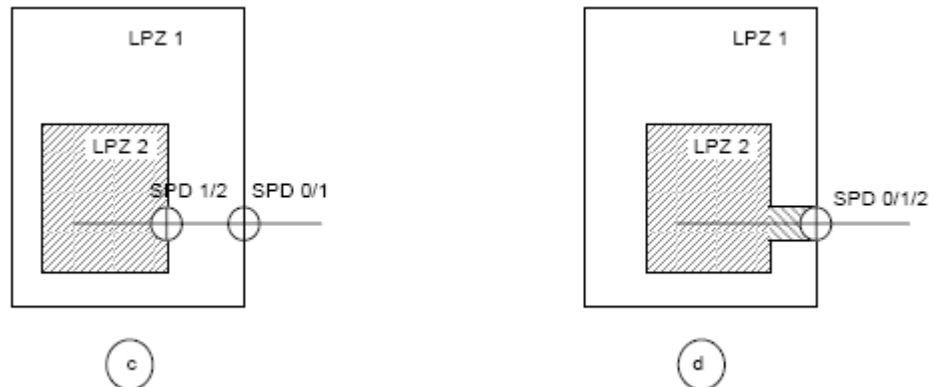


Fig.53c) Two coordinated SPD (0/1) and SPD (1/2) needed

NOTE Figure 53c) shows an LPZ 2 supplied by an electrical or signal line. This line needs two coordinated SPDs: one at the boundary of LPZ 1, the other at the boundary of LPZ 2.

Fig. 53d) Only one SPD (0/1/2) needed (LPZ 2 extended into LPZ 1)

NOTE Figure 53d) shows that the line can enter immediately into LPZ 2 and only one SPD is required, if LPZ 2 is extended into LPZ 1 using shielded cables or shielded cable ducts.

However this SPD will reduce the threat immediately to the level of LPZ 2.

Fig.53 Examples for extended lightning protection zones

3.2 Basic protection measures in an LPMS

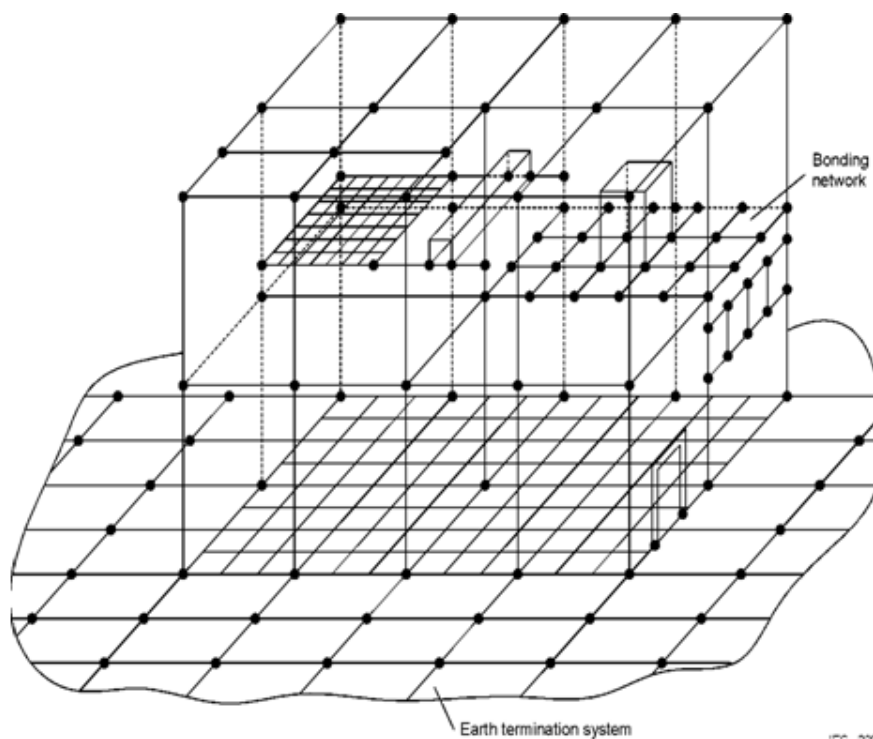
Basic protection measures against LEMP include:

3.2.1 Earthing and bonding

- The earthing system conducts and disperses the lightning current into the earth.
- The bonding network minimizes potential differences and may reduce magnetic field.

Suitable earthing and bonding is based on a complete earthing system (see Figure 54) combining:

the earth-termination system (dispersing the lightning current into the soil) and the bonding network (minimizing potential differences and reducing the magnetic field).



NOTE All drawn connections are either bonded structure metal elements or bonding connections. Some of them may also serve to intercept, conduct and disperse the lightning current into the

Fig.54 Example of a three-dimensional earthing system consisting of the bonding network interconnected with the earth termination system

- **Earth termination system**

The earth termination system of the structure shall comply with IEC 62305-3. In structures where only electrical systems are provided, a Type A earthing arrangement may be used, but a Type B earthing arrangement is preferable. In structures with electronic systems a Type B earthing arrangement is recommended.

The ring earth electrode around the structure, or the ring earth electrode in the concrete at the perimeter of the foundation, should be integrated with a meshed network under and around the structure, having a mesh width of typically 5 m. This greatly improves the performance of the earth termination system. If the basement's reinforced concrete floor forms a well defined interconnected mesh and is connected to the earth termination system, typically every 5 m, it is also suitable. An example of a meshed earth termination system of a plant is shown in Figure 55.

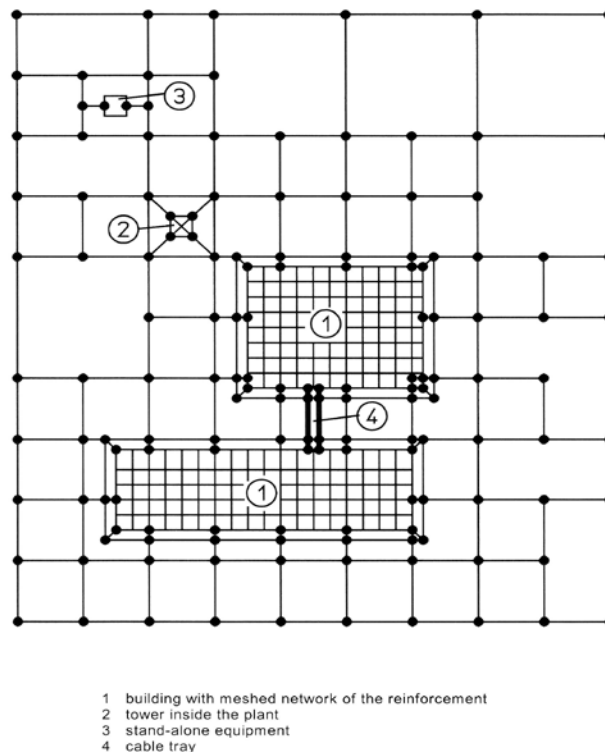


Fig.55 Meshed earth termination system of a plant

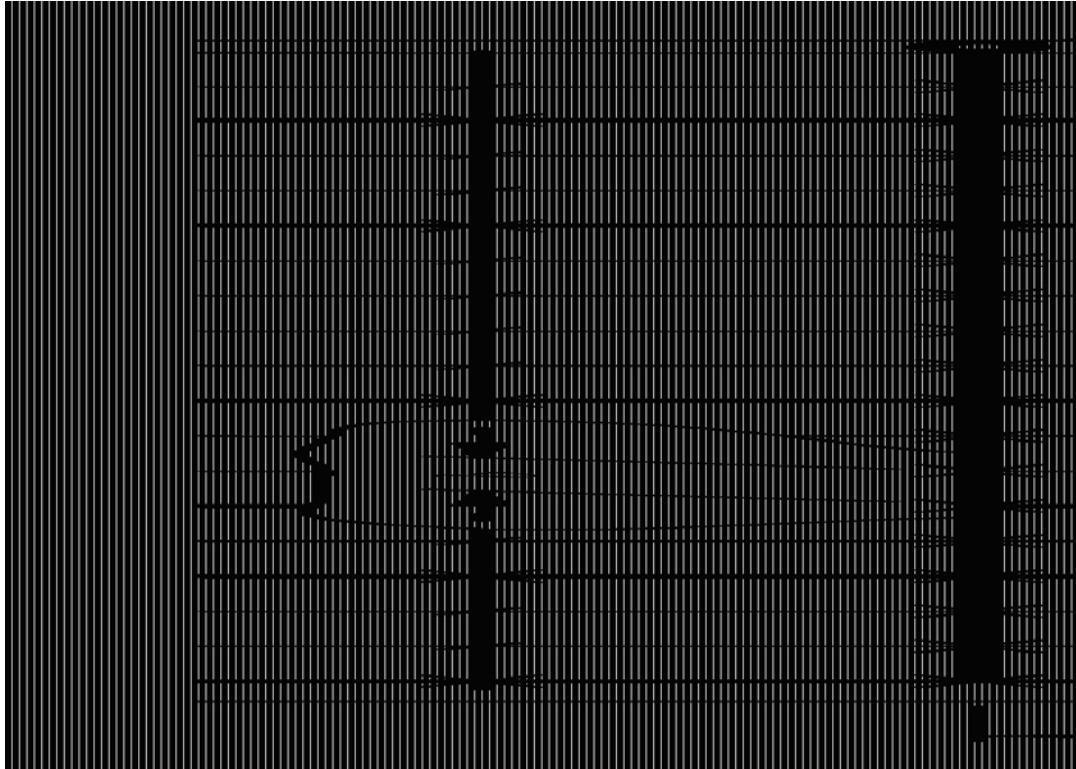
- **Bonding network**

A low impedance bonding network is needed to avoid dangerous potential differences between all equipment inside the inner LPZ. Moreover, such a bonding network also reduces the magnetic field.

This can be realized by a meshed bonding network integrating conductive parts of the structure, or parts of the internal systems, and by bonding metal parts or conductive services at the boundary of each LPZ directly or by using suitable SPDs.

The bonding network can be arranged as a three-dimensional meshed structure with a typical mesh width of 5 m. This requires multiple interconnections of metal components in and on the structure (such as concrete reinforcement, elevator rails, cranes, metal roofs, metal facades, metal frames of windows and doors, metal floor frames, service pipes and cable trays). Bonding bars (e.g. ring bonding bars, several bonding bars at different levels of the structure) and magnetic shields of the LPZ shall be integrated in the same way.

Examples of bonding networks are shown in Figures 56 and 57.



Key

- 1 air termination conductor
- 2 metal covering of the roof parapet
- 3 steel reinforcing rods
- 4 mesh conductors superimposed on the reinforcement
- 5 joint of the mesh conductor
- 6 joint for an internal bonding bar
- 7 connection by welding or clamping
- 8 arbitrary connection
- 9 steel reinforcement in concrete (with superimposed mesh conductors)
- 10 ring earthing electrode (if any)
- 11 foundation earthing electrode
- a* typical distance of 5 m for superimposed mesh conductors
- b* typical distance of 1 m for connecting this mesh with the reinforcement

Fig. 56 Utilization of reinforcing rods of a structure for equipotential bonding

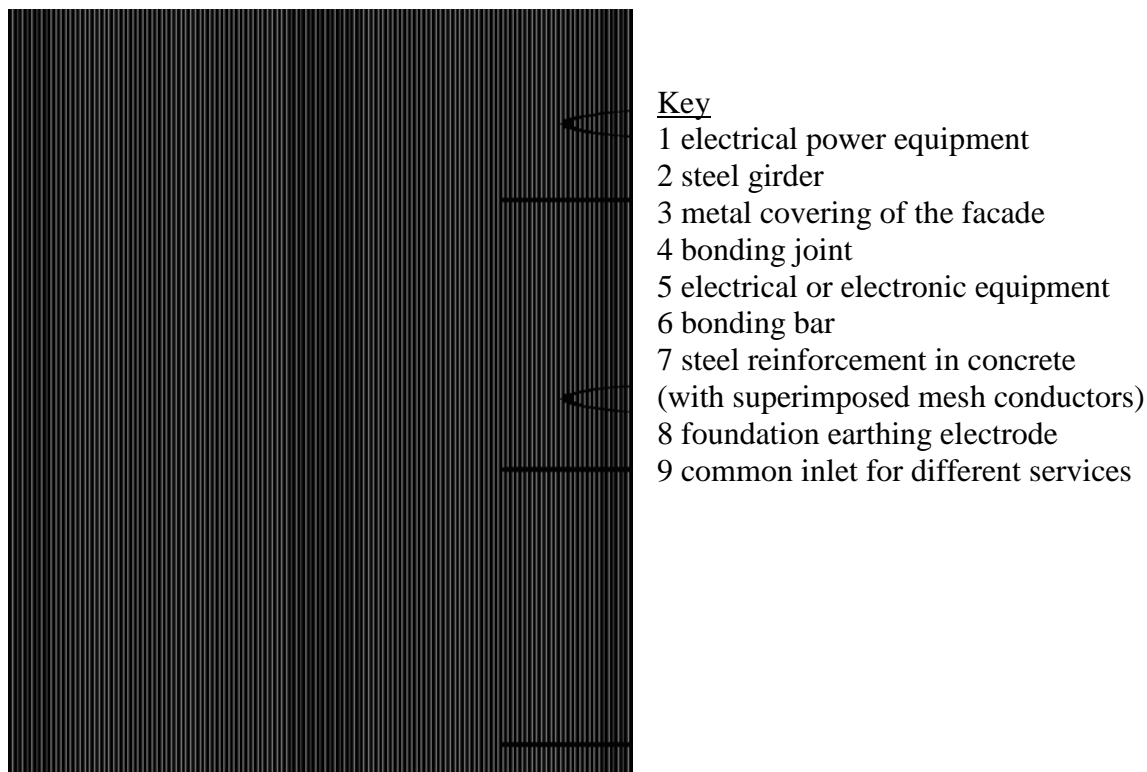


Fig. 57 Equipotential bonding in a structure with steel reinforcement

Conductive parts (e.g. cabinets, enclosures, racks) and the protective earth conductor (PE) of the internal systems shall be connected to the bonding network according to the following configurations (see Figure 58):

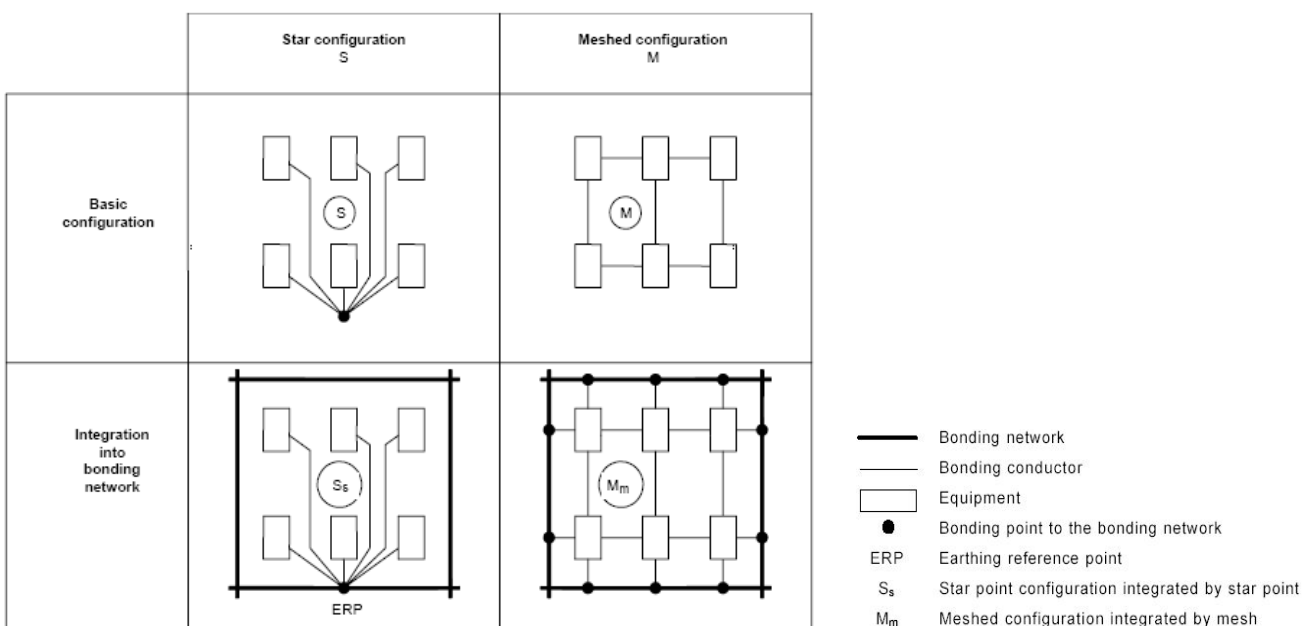


Fig. 58 Integration of electronic systems into the bonding network

If the configuration S is used, all metal components (e.g. cabinets, enclosures, racks) of the internal systems shall be isolated from the earthing system. The configuration S shall be integrated into the earthing system only by a single bonding bar acting as the earth reference point (ERP) resulting in type Ss. When configuration S is used, all lines between the individual equipment shall run in parallel with the bonding conductors following the star configuration in order to avoid induction loops. Configuration S can be used where internal systems are located in relatively small zones and all lines enter the zone at one point only.

If configuration M is used, the metal components (e.g. cabinets, enclosures, racks) of the internal systems are not to be isolated from the earthing system, but shall be integrated into it by multiple bonding points, resulting in type Mm. Configuration M is preferred for internal systems extended over relatively wide zones or over a whole structure, where many lines run between the individual pieces of equipment, and where the lines enter the structure at several points.

In complex systems, the advantages of both configurations (configuration M and S) can be combined as illustrated in Figure 59, resulting in combination 1 (Ss combined with Mm) or in combination 2 (Ms combined with Mm).

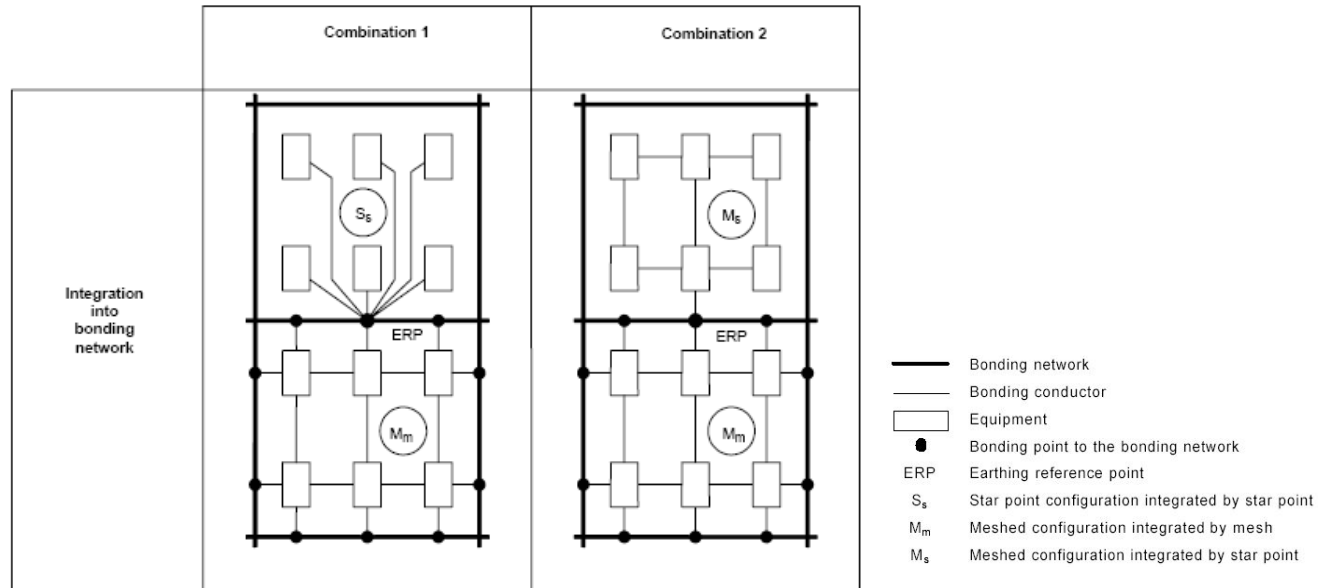


Fig.59 Combinations of integration methods of electronic systems into the bonding network

• Bonding bars

Bonding bars shall be installed for bonding of

- all conductive services entering a LPZ (directly or by using suitable SPDs),
- the protective earth conductor PE,
- metal components of the internal systems (e.g. cabinets, enclosures, racks),
- the magnetic shields of the LPZ at the periphery and inside the structure.

For efficient bonding the following installation rules are important:

- the basis for all bonding measures is a low impedance bonding network;
- bonding bars should be connected to the earthing system by shortest possible route (using bonding conductors not longer than 0,5 m);
- material and dimensions of bonding bars and bonding conductors;

- SPD should use the shortest possible connections to the bonding bar as well as to the live conductors thus minimizing inductive voltage drops;
- on the protected side of the circuit (after an SPD), mutual induction effects should be minimized, either by minimizing the loop area or using shielded cables or cable ducts.

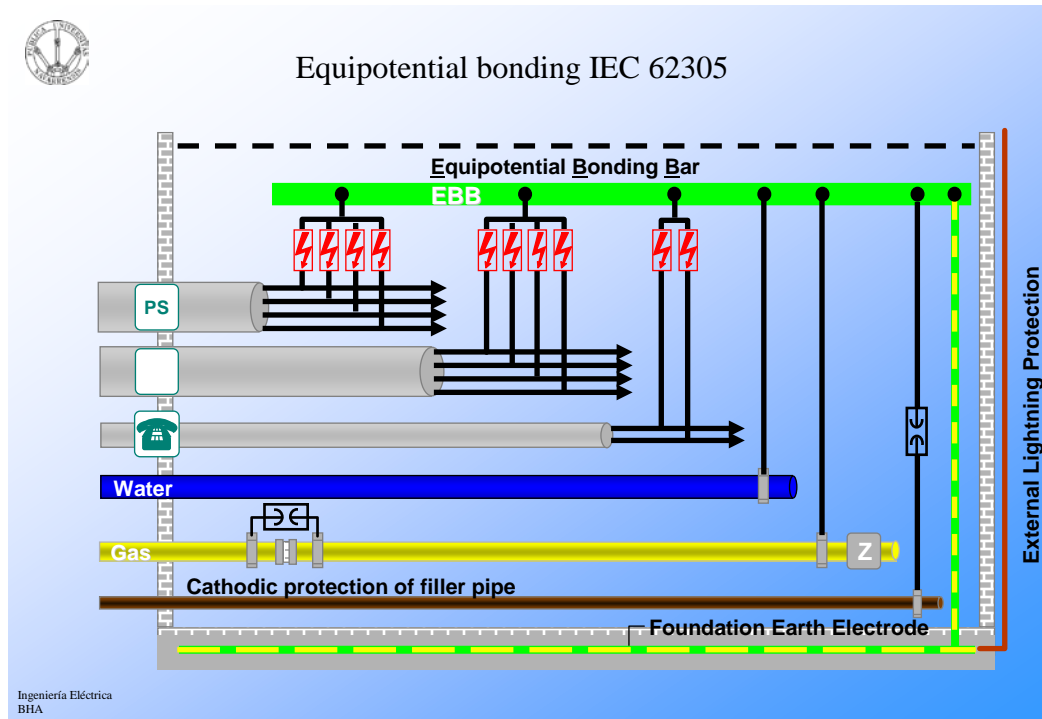


Fig.60 Bonding bar

3.2.2 Magnetic shielding and line routing

- Magnetic shielding can reduce the electromagnetic field as well as the magnitude of induced internal surges.
- Suitable routing of internal lines can also minimize the magnitude of induced internal surges. Both measures are effective in reducing permanent failure of internal systems.

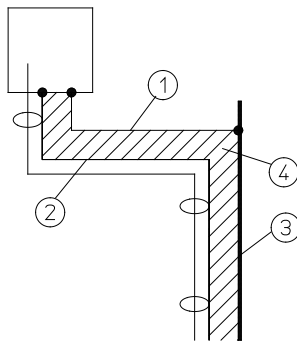
a) Protection measures by line routing and shielding

Suitable line routing and shielding are effective measures to reduce induced overvoltage.

These measures are especially important, if the spatial shielding effectiveness of LPZ 1 is negligible. In this case, the following principles provide improved protection:

- minimizing the induction loop area;
- powering new equipment from the existing mains should be avoided, because it creates a large enclosed induction loop area, which will significantly increase the risk of isolation damage.
- using shielded cables – the shields of these signal lines should at least be bonded at either end.
- using metal cable ducts or bonded metal plates – the separate metal sections should be electrically well interconnected. The connections should be performed by bolting the overlapping parts or by using bonding conductors. In order to keep the impedance of the cable duct low, multiple screws or strips should be distributed over the perimeter of the cable duct.

Examples of good line routing and shielding techniques are given in Figures 61 and 62

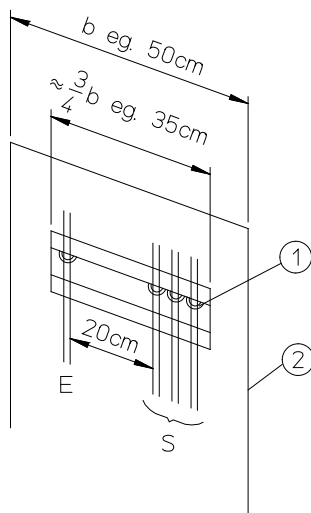


Key

- 1 PE, only when Class I equipment is used
- 2 optional cable shield needs to be bonded at both ends
- 3 metal plate as additional shield
- 4 small loop area

NOTE Owing to the small loop area, the induced voltage between the cable shield and the metal plate is small.

Fig.61 Reduction of loop area using shielded cables close to a metal plate



Key

- 1 cable fixing with or without bonding of cable shields to the plate
- 2 at edges, the magnetic field is higher than in the middle of the plate
- E electrical lines
- S signal lines

Fig. 62 Example of a metal plate for additional shielding

• **Spatial shielding**

Spatial shields define protected zones, which may cover the whole structure, a part of it, a single room or the equipment enclosure only. These may be grid-like, or continuous metal shields, or comprise the "natural components" of the structure itself.

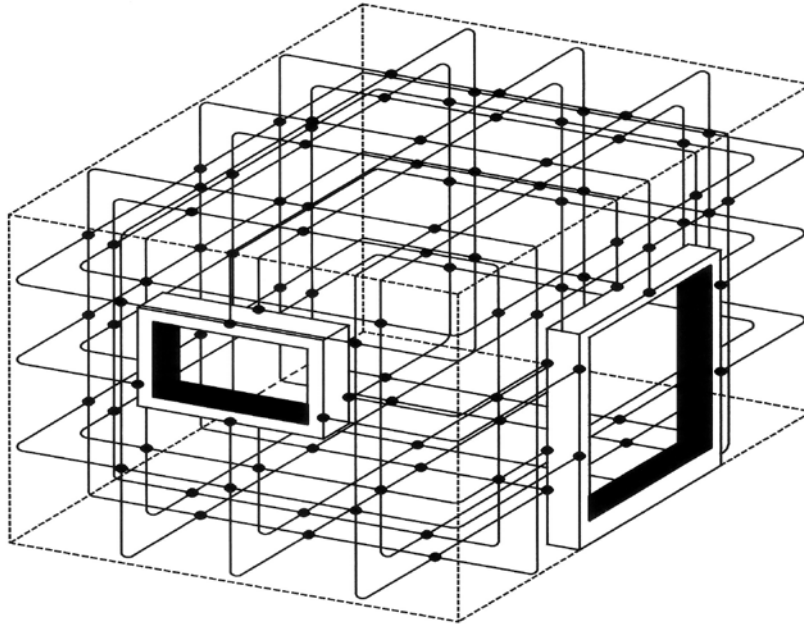
Spatial shields are advisable where it is more practical and useful to protect a defined zone of the structure instead of several individual pieces of equipment.

Spatial shields should be provided in the early planning stage of a new structure or a new internal system. Retrofitting to existing installations may result in higher costs and greater technical difficulties.

- **Grid-like spatial shields**

In practice, the large volume shields of LPZs are usually created by natural components of the structure such as the metal reinforcement in the ceilings, walls and floors, the metal framework, the metal roofs and metal facades. These components together create a grid-like spatial shield. Effective shielding requires that the mesh width be typically less than 5 m.

Figure 63 shows how in practice the metal reinforcement in concrete and metal frames (for metal doors and possibly shielded windows) can be used to create a large volume shield for a room or building.



- **Welded or clamped at every rod and at the crossings**

Fig. 63 Large volume shield built by metal reinforcement and metal frames

Electronic systems shall be located inside a "safety volume" which respects a safety distance from the shield of the LPZ (see Figure 64). This is because of the relatively high magnetic fields close to the shield, due to partial lightning currents flowing in the shield (particularly for LPZ 1).

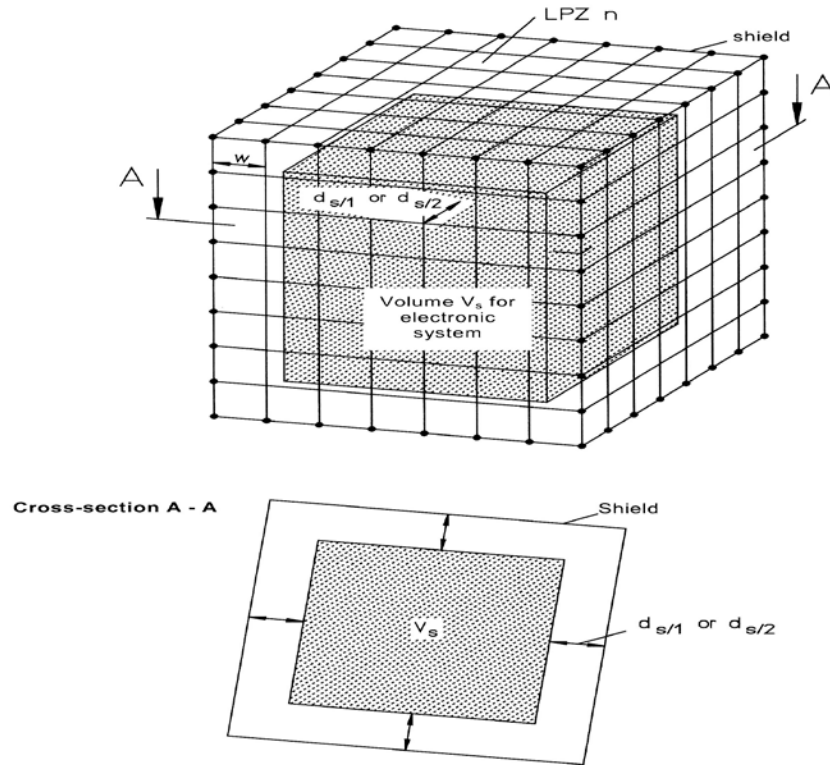


Fig. 64 Volume for electrical and electronic systems inside an inner LPZ n

- **Shielding of internal lines**

Shielding may be restricted to cabling and equipment of the system to be protected: metallic shield of cables, closed metallic cable ducts and metallic enclosure of equipment are used for this purpose.

- **Routing of internal lines**

Suitable routing of internal lines minimizes induction loops and reduces the creation of surge voltages internal to the structure. The loop area can be minimized by routing the cables close to natural components of the structure which have been earthed and/or by routing electrical and signal lines together.

- **Shielding of external lines**

Shielding of external lines entering the structure includes cable shields, closed metallic cable ducts and concrete cable ducts with interconnected reinforcement steel. Shielding of external lines is helpful, but often not within the responsibility of the LPMS planner (since the owner of external lines is normally the network provider).

Particular attention should be paid when installing cables close to the shield of an LPZ (especially LPZ 1) due to the substantial value of the magnetic fields at that location.

When cables, which run between separate structures, need to be protected, they should be run in metal cable ducts. These ducts should be bonded at both ends to the bonding bars of the

separate structures. If the cable shields (bonded at both ends) are able to carry the anticipated partial lightning current, additional metal cable ducts are not required.

Fig.65a) Unprotected system

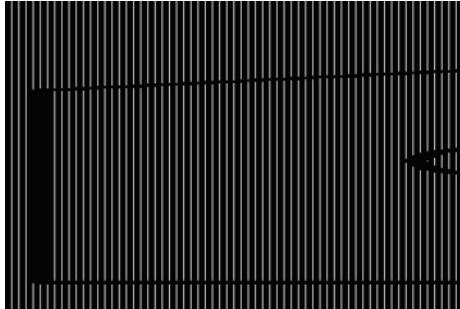


Fig. 65b) Reducing the magnetic field inside an inner LPZ by its spatial shield

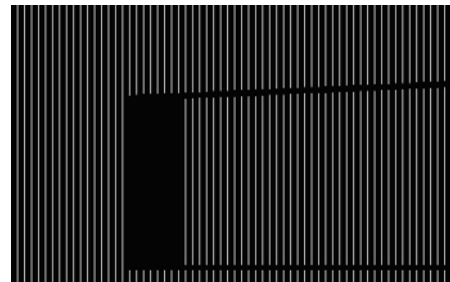


Fig.65c) Reducing the influence of the field on lines by line shielding

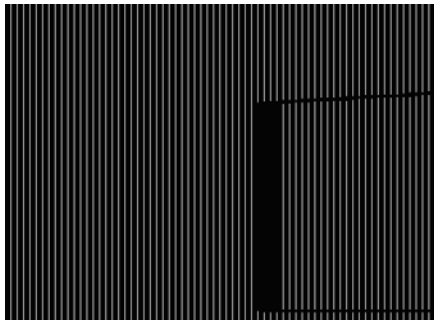
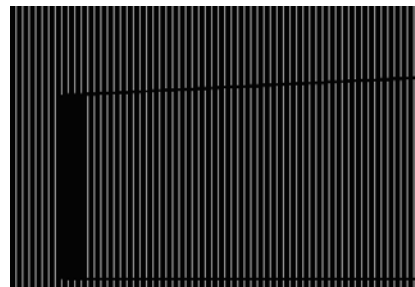


Fig.65d) Reducing the induction loop area by suitable line routing



Key

- 1 Device in metal housing
- 2 Power line
- 3 Data line

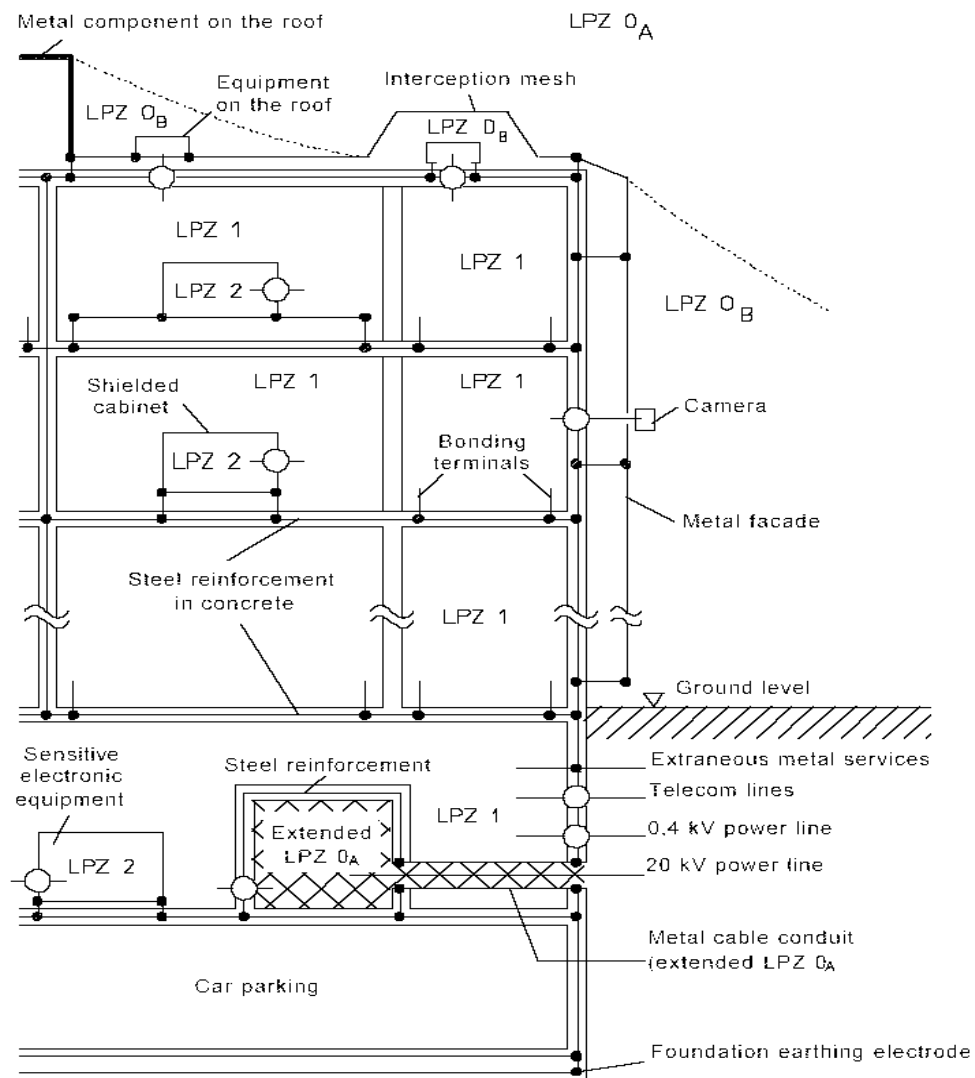
- 4 Induction loop
- 5 External spatial shielding
- 6 Metallic shield of line

Fig. 65 Reducing induction effects by line routing and shielding measures

Figure 66 provides an example of a large office building:

-Shielding is achieved by steel reinforcement and metal facades for LPZ 1, and by shielded enclosures for the sensitive electronic systems in LPZ 2. To be able to install a narrow meshed bonding system, several bonding terminals are provided in each room.

-LPZ 0 is extended into LPZ 1 to house a power supply of 20 kV, because the installation of SPDs on the high voltage power side immediately at the entrance was not possible in this special case.



- Equipotential bonding
- Surge protective device (SPD)

Fig.66 Example of an LPMS for an office building

b) Reduction of overvoltage in cables

High induced voltages and currents can be prevented by running cables in bonded ducting, trucking or metal tubes. All cables leading to the specific equipment should leave the cable duct at a single point. Where possible, the inherent shielding properties of the structure itself should be used to maximum advantage by running all cables together within the tubular components of the structure. Where this is not possible, as in the case of process vessels, cables should run on the outside but close to the structure and make as much use as possible of the natural shielding provided by metal pipes, steel rung ladders and any other well bonded conducting materials (see Figure 67). On masts which use L-shaped corner members, cables should be placed in the inside corner of the L for maximum protection (see Figure 68).

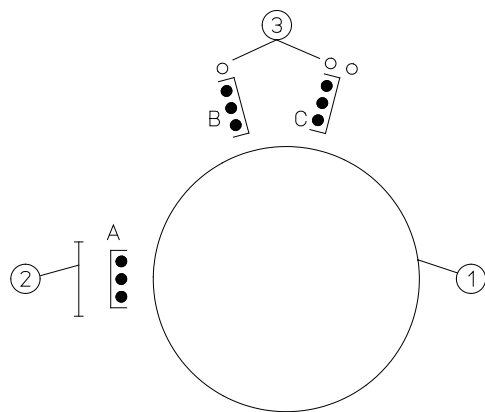
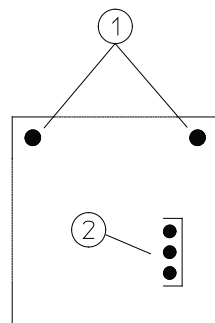


Fig.67 Inherent shielding provided by bonded ladders and pipes



Key
 1 ideal positions for cables in corners of L-girders
 2 alternative position for bonded cable tray within the mast

Fig. 68 Ideal positions for lines on a mast (cross-section of steel lattice mast)

3.2.3 Coordinated SPD protection

a) General

SPD is device intended to limit transient overvoltages and divert surge currents.

Where two or more SPDs are installed one after another in the same circuit, they shall be coordinated in such a way as to share the energy between them according to their energy absorbing capability.

In an LPMS using the lightning protection zones concept with more than one LPZ (LPZ 1, LPZ 2 and higher), SPD(s) shall be located at the line entrance into each LPZ.

In an LPMS using LPZ 1 only, SPD shall be located at the line entrance into LPZ 1 at least.

In both cases, additional SPDs may be required if the distance between the location of the SPD and the equipment is being protected is long.

b) Type of SPD

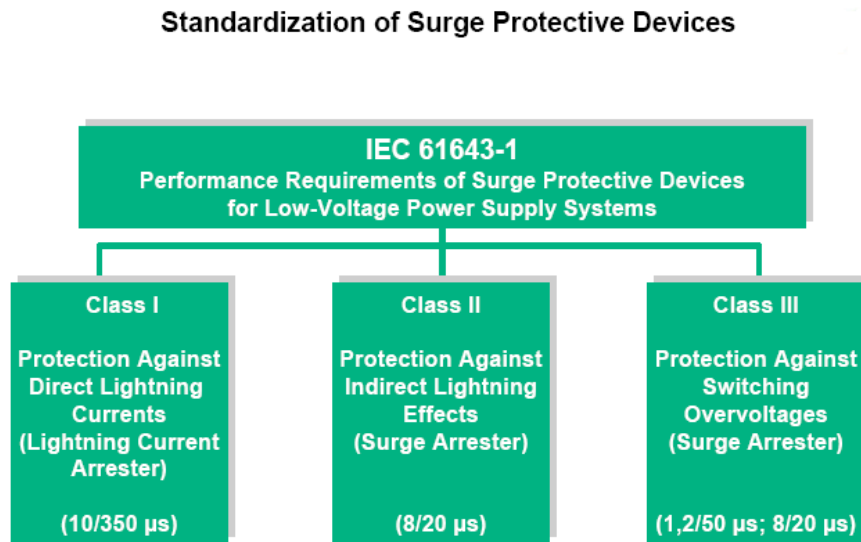


Fig.69 Types of surge protection device

- **Type 1 surge protectors**

They protect low-voltage installations against surge voltage also in case of direct lightning strikes. Type 1 surge protectors are designed to be installed where a direct lightning strike risk is high, especially when the building is equipped with external lightning protection system (LPS or lightning rod). These products are installed at the entrance of the installation (such as main distribution board). These protectors are tested following the Class I test based on 10/350μs impulse current injection in order to simulate the direct lightning strike consequence. Therefore these Type 1 surge protectors must be especially powerful to conduct this high energy impulse current.

- **Type 2 surge protectors**

They provide protection against surge voltages due to distant lightning strikes or peak voltages arising in the electrical power system.

Type 2 surge protectors are designed to be installed in the sub-distribution board, at the beginning of the installation, or close to sensitive terminals, on installations without LPS (lightning rods). These protectors are tested following the Class II test based on 8/20μs impulse current injection.

- **Type 3 surge protectors**

Surge protection devices are installed at the terminal equipment absorbing the residual energy and providing protection against surges due to internal switching operations. Type 3 SPDs are tested with a combination waveform (1,2/50 μs - 8/20μs) following Class III test.

The power of the induced surges and the resulting impulse currents is considerably lower than the power of a direct lightning impulse current and is therefore only described with the impulse current wave 8/20 μ s (Fig. 70). Components and equipment, which do not have to carry currents out of direct lightning strikes, are therefore tested with impulse currents of 8/20 μ s.

The characteristic parameters of flowing impulse currents (peak value, rate of current rise, load, specific energy) can be described with the impulse-current wave form 10/350 μ s (Fig. 70) and are defined in international standards as test currents for components and devices for the protection against direct lightning strikes.

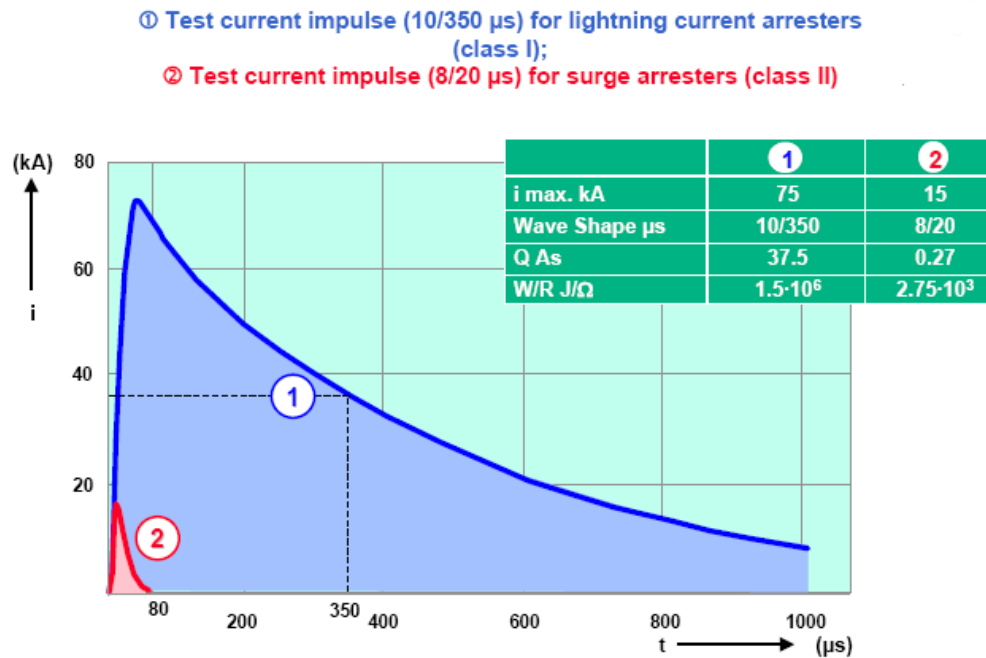


Fig.70 Wave shape of Lightning and current arrester

c) Application of SPD

Figure 71 shows an example of the application of SPDs in power distribution systems according to the lightning protection zones concept. The SPDs are installed in sequence. They are chosen according to the requirements at their particular installation point.

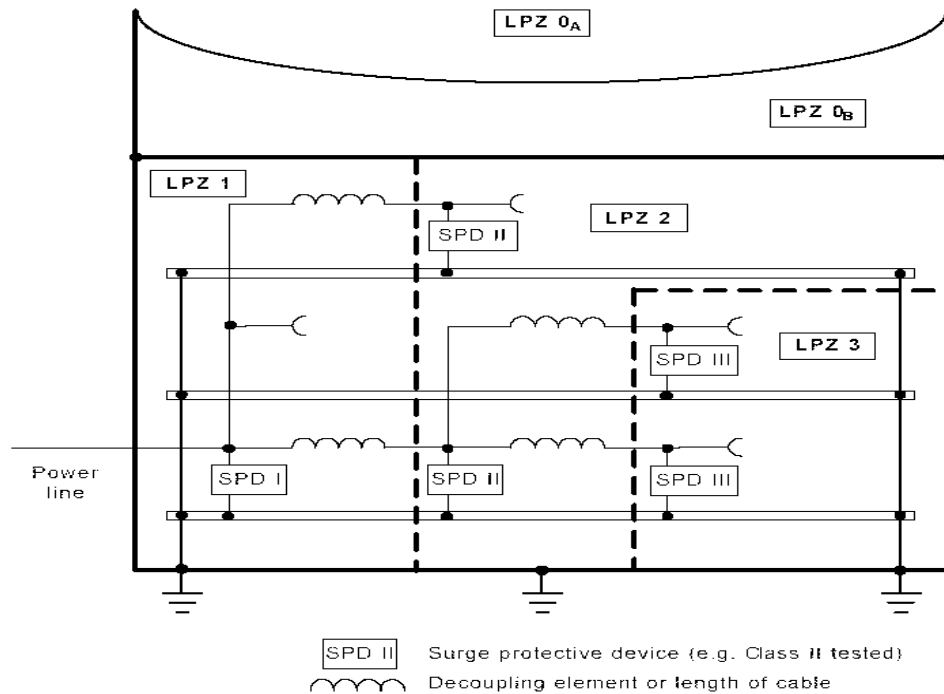


Fig. 71 Example for the application of SPD in power distribution system according to the lightning protection zones concepts

Once the majority of the energy of the partial lightning current has been diverted via the first SPD, the subsequent SPDs need to be designed only to cope with the remaining threat from the interface LPZ 0A to LPZ 1 plus the induction effects from the electromagnetic field within LPZ 1 (especially if LPZ 1 has no electromagnetic shield).

Lines entering from LPZ 0A (where direct flashes are possible) carry partial lightning currents. At the interface LPZ 0A to LPZ 1 therefore, SPDs tested with Iimp (Class I tested SPD) are needed to divert these currents.

Lines entering from LPZ 0B (where direct flashes are excluded but the full electromagnetic field exists), carry only induced surges. At the interface LPZ 0B to LPZ 1 the induced effects should be simulated by means of either a surge current with a waveshape 8/20 μ s (Class II tested SPD) or an adequate combination wave test (Class III tested SPD) .

The remaining threat at the zone transition LPZ 0 to LPZ 1 and the induced effects of the electromagnetic field within LPZ 1 define the requirements for the SPDs at the interface LPZ 1 to LPZ 2. If no detailed analysis of the threat is possible, the dominant stress should be simulated by means of either a surge current with a waveshape 8/20 μ s (Class II tested SPD) or combination wave test (Class III tested SPD) .

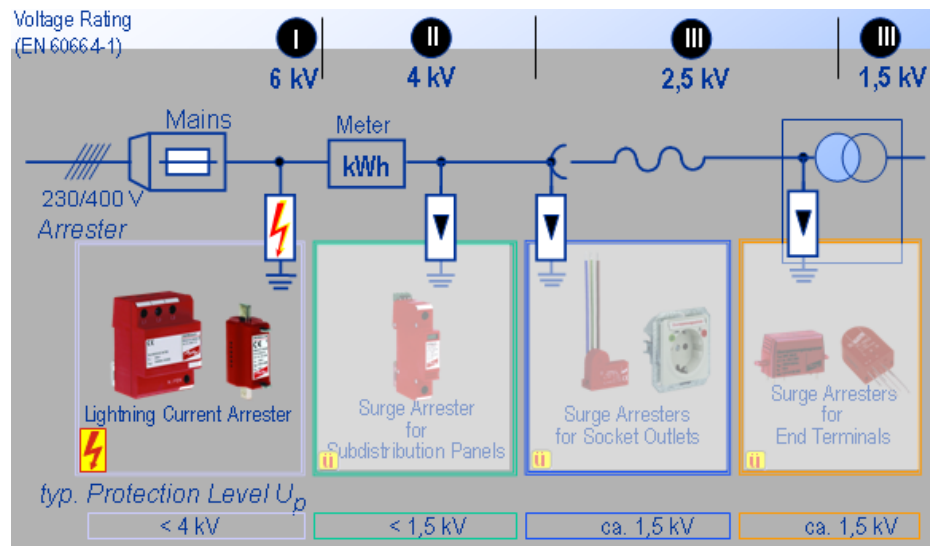


Fig. 72 Application of lightning and surge arresters according to impulse voltage rating

Selection of the Protection Level according to impulse voltage rating :

Nominal Voltage of the Power Supply		Impuls Voltage Rating			
3-Phase System, Starpoint grounded	1-Phase	Equipment used at the Main Entrance of the fixed installation (Surge Category I)	Equipment as a part of the fixed installation (Surge Category II)	Equipment to be connected to the fixed installation (Sure Category III)	Special equipment to be protected (Surge Category IIII)
	120 to 240	4	2,5	1,5	0,8
230/400		6	4	2,5	1,5
277/480		8	6	4	2,5
400/690		Values are fixed on the special project requirements., if nothing is defined, the values for 400/690 V systems shall be used			
1000					
*) Nach IEC 38					

Fig.73 Selection of the Protection Level

d) General objectives of SPD coordination

Figure 74 illustrates the basic model of the energy coordination for SPDs. This model is only valid when the impedance of the bonding network and the mutual inductance between the bonding network and the installation formed by the connection of SPD 1 and SPD 2, is negligible.

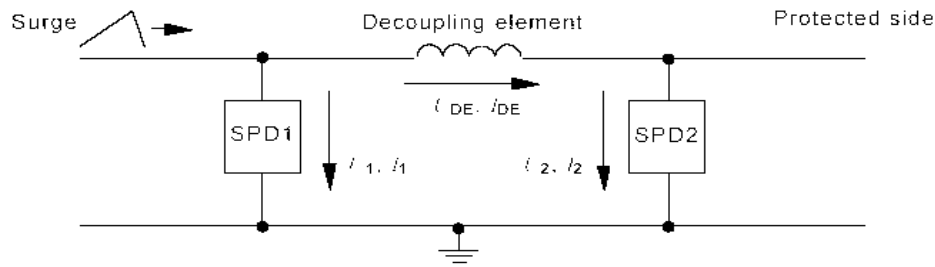


Fig.74 Basic model for energy coordination of SPD

A decoupling element must be installed for subsequent installation of lightning current arrester and surge arrester with cable lengths under 15 metres.

A lightning current arrester is fitted at the power entry panel of the facility, followed by a decoupling element, terminating in a class 2 surge arrester at the power distribution board.

e) Coordination principles

The coordination between SPDs can be achieved by using one of the following principles:

- Coordination of the voltage/current characteristics (without decoupling elements).

This method is based on the voltage/current characteristic and is applicable to voltage limiting type SPDs (e.g. MOV or suppressor diodes). This method is not very sensitive to the current waveshape.

- Coordination using dedicated decoupling elements

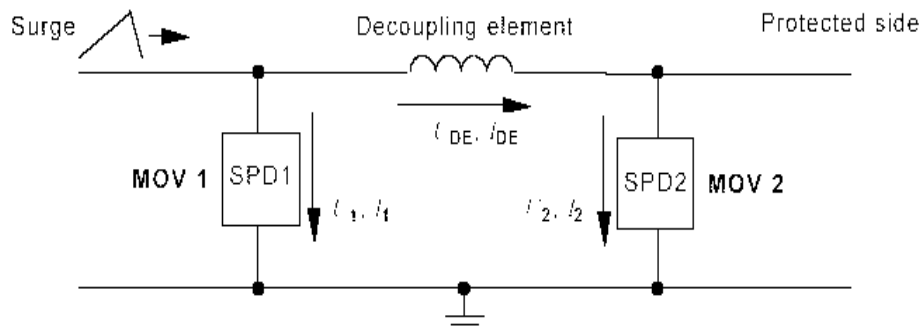
For coordination purposes, additional impedances with sufficient surge withstand capability can be used as decoupling elements. Resistive decoupling elements are primarily used in information systems. Inductive decoupling elements are primarily used for power systems. For the coordination efficiency of inductances the current steepness di/dt is the decisive parameter.

- Coordination using triggered SPDs (without decoupling elements).

Coordination can also be achieved using triggered SPDs if the electronic trigger circuit can assure that the energy withstand capability of subsequent SPDs is not exceeded.

- Coordination of two voltage-limiting type SPDs

Figure 75a) shows the basic circuit diagram for the coordination of two voltage-limiting type SPDs.



Key

MOV metal oxide varistor

Fig.75a) Circuit with two voltage-limiting type SPDs

Figure 75b) illustrates the energy dispersion within the circuit. The total energy feed into the system increases with the growing impulse current. As long as the energy dissipated in each of the two SPDs does not exceed their energy withstand capability, coordination is achieved.

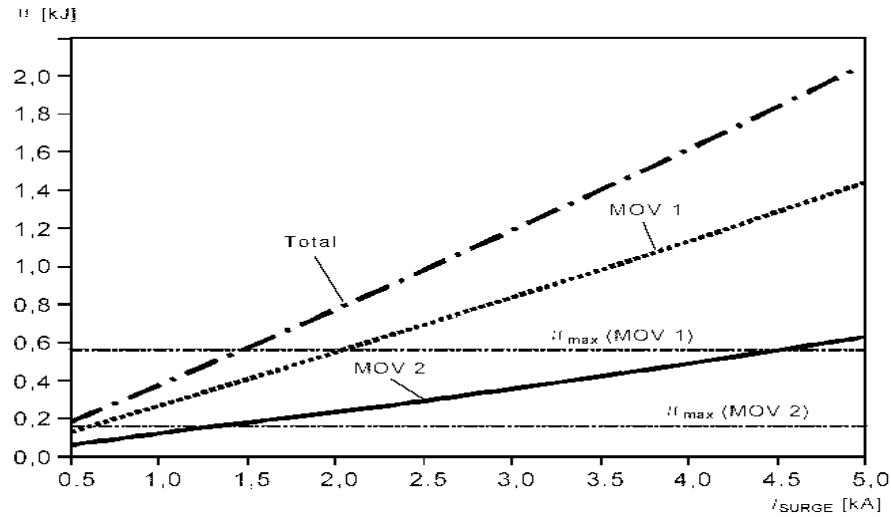


Fig.75b) Principles of energy coordination between MOV 1 and MOV 2

Fig.75 Combination of two voltage-limiting type SPDs

If two voltage-limiting type SPDs are coordinated, both shall be dimensioned for their respective surge current and energy. The duration of the current wave considered will be as long as that of the impinging current. Figures 76a) and 76b) provide an example of the energy coordination between two voltage-limiting type SPDs in the case of a 10/350 μ s surge.

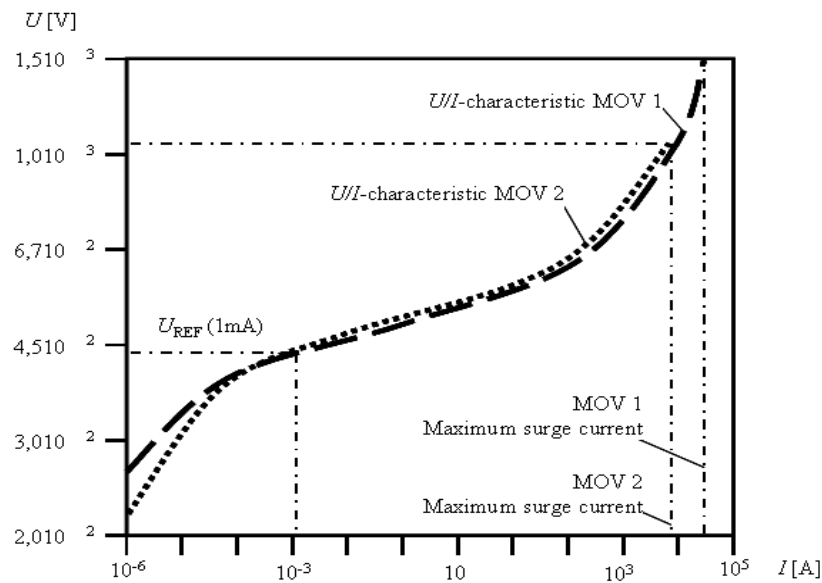


Fig. 76a) Current/voltage characteristics of MOV 1 and MOV 2

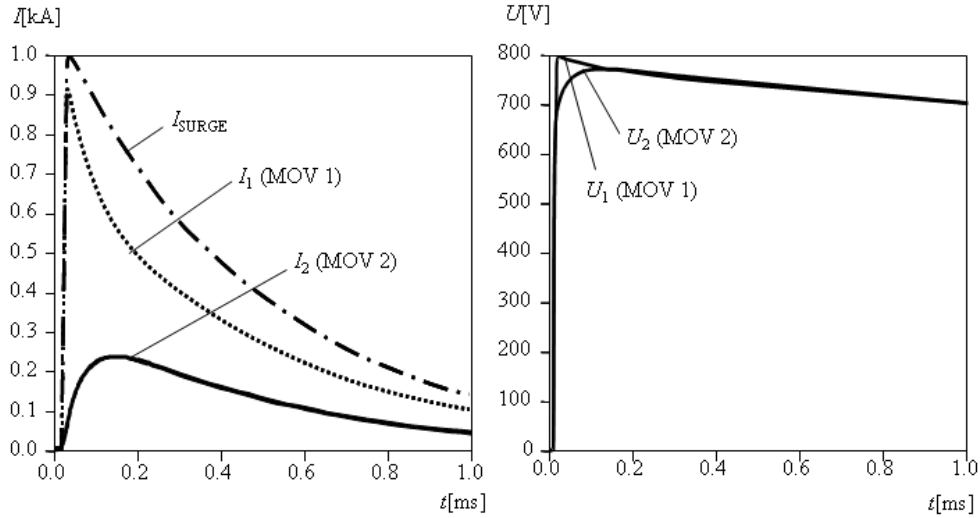


Fig. 76b) Current and voltage characteristics at MOV 1 and MOV 2 from 10/350 μ s surge

Fig. 76 Example with two voltage-limiting type MOV 1 and MOV 2

- **Coordination between voltage switching type and voltage limiting type SPDs**

Figure 77a) shows the basic circuit diagram of this coordination variant using a spark gap (SPD 1) and a MOV (SPD 2) as example technologies

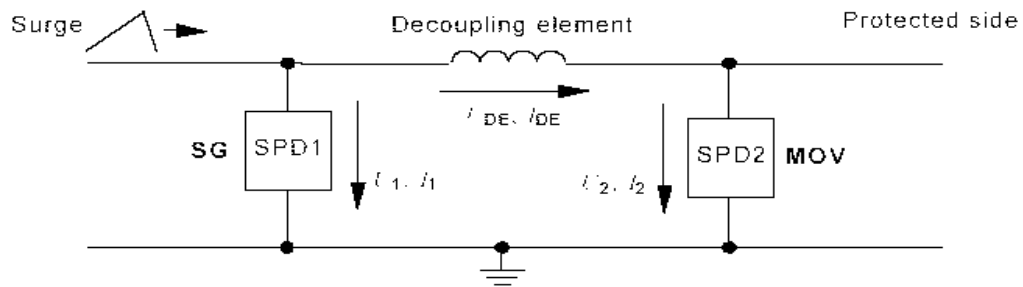


Fig.77a) Circuit with spark gap and MOV

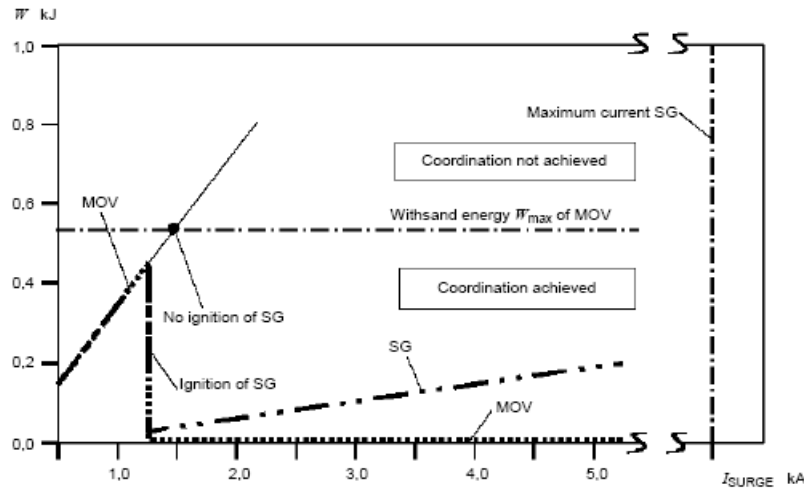


Fig.77b) Principle for energy coordination of a spark gap and a MOV

Fig.77 Combination of voltage-switching type spark gap and voltage-limiting type MOV

The ignition of the spark gap (SPD 1) depends on the sum of the residual voltage U_{res} across the MOV (SPD 2) and of the dynamic voltage drop across the decoupling element U_{DE} . As soon as the voltage U_1 exceeds the dynamic spark over voltage U_{SPARK} , the spark gap will ignite and coordination is achieved. This depends only on the :

- characteristics of the MOV,
- steepness and magnitude of the incoming surge current,
- decoupling element (inductance or resistance).

Two basic situations should be considered:

- No ignition of the spark gap (Figure 78a)):

If the spark gap does not ignite, the complete surge current flows through the MOV. As shown in Figure 77 b) the coordination has not been achieved, if the energy dissipated by this surge is higher than the withstand energy of the MOV. If an additional inductance is required as the decoupling element, coordination should be evaluated using the worst-case minimum current steepness of 0,1 kA/ μ s.

- Ignition of the spark gap (Figure 78b)):

If the SG does ignite, the duration of the current flowing through the MOV is considerably reduced. As shown in Figure 77 b) the proper coordination is achieved when the spark gap ignites before the withstand energy of the MOV is exceeded.

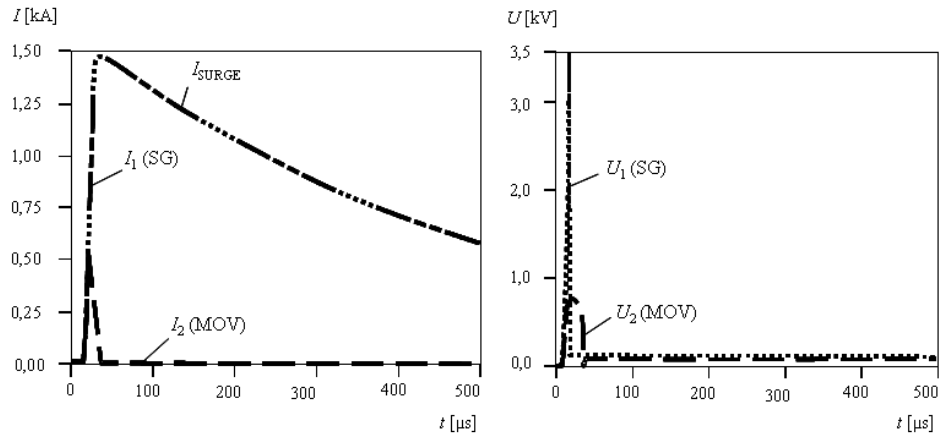


Fig.78a) Current and voltage of spark gap and MOV from a 10/350 μ s surge (SPD 1 not ignited)

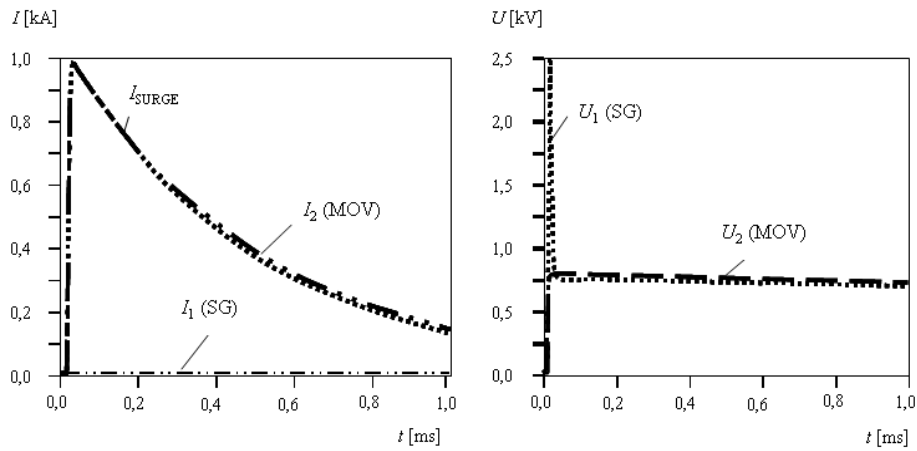


Fig.78b) Current and voltage of spark gap and MOV from a 10/35 μ s surge (SPD 1 ignited)

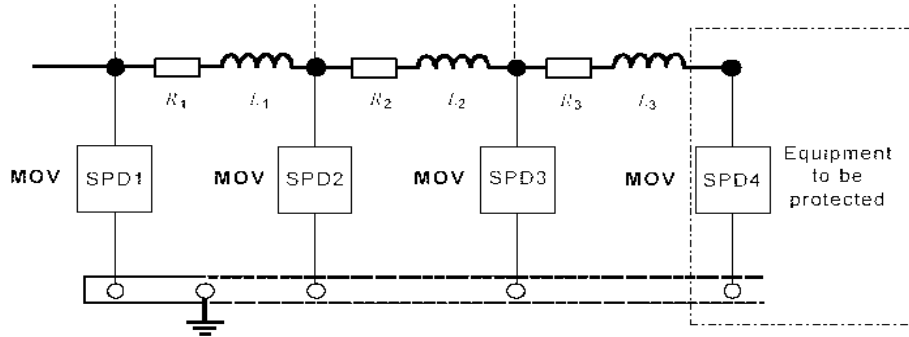
Fig.78 Example with voltage-switching type spark gap and voltage-limiting type MOV

f) Basic coordination variants for protection systems

There are four coordination variants for protection systems: The first three use one-port SPDs, whereas the fourth uses two-port SPDs with integrated decoupling elements. These coordination variants should be considered (also taking into account SPDs integrated in the equipment to be protected).

- **Variant I**

All SPDs have a continuous voltage/current characteristic (e.g. MOVs or suppressor diodes) and the same residual voltage U_{RES} . The coordination of the SPDs and of the equipment to be protected is normally achieved by the impedances of lines between them (see Figure 79).

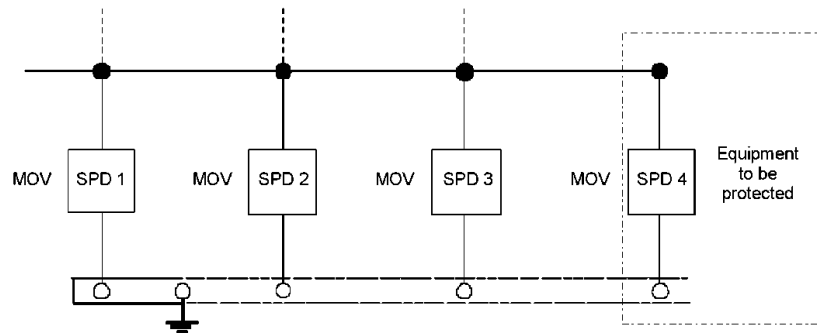


$$U_{RES} (SPD 1) = U_{RES} (SPD 2) = U_{RES} (SPD 3) = U_{RES} (SPD 4)$$

Fig.79 Coordination variant I – Voltage-limiting type SPD

- **Variant II**

All SPDs have a continuous voltage/current characteristic (e.g. MOVs or suppressor diodes). The residual voltage U_{RES} raises stepwise from SPD 1 to SPD 3 (see Figure 80). This is a coordination variant for power supply systems.



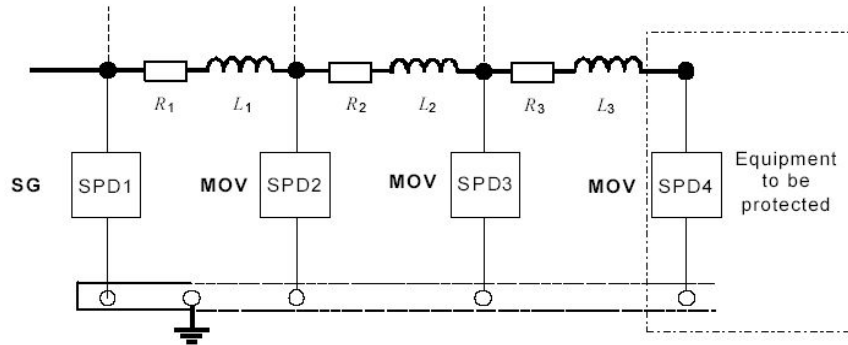
$$U_{RES} (SPD 1) < U_{RES} (SPD 2) < U_{RES} (SPD 3) < U_{RES} (SPD 4)$$

Fig. 80 Coordination variant II – Voltage-limiting type SPD

- **Variant III**

SPD 1 has a discontinuous voltage/current characteristic (e.g. spark gaps). Subsequent SPDs have a continuous voltage/current characteristic (e.g. MOVs or suppressor diodes). All SPDs have the same residual voltage U_{RES} (see Figure 81).

The characteristic of this variant is, that by the switching behaviour of SPD 1, a reduction of the time to half value of the original current impulse $10/350 \mu s$ will be achieved, which relieves the subsequent SPDs considerably.



$$U_{RES} (SPD 1) = U_{RES} (SPD 2) = U_{RES} (SPD 3) = U_{RES} (SPD 4)$$

Fig.81 Coordination variant III – Voltage-switching type SPD and voltage-limiting type SPD

- **Variant IV**

Two-port SPDs are available which incorporate cascaded stages of SPDs internally coordinated with series impedances or filters. Successful internal coordination ensures minimum energy transfer to downstream SPDs or the equipment. These SPDs should be fully coordinated with other SPD in the system in accordance with variant I, II or III as appropriate.

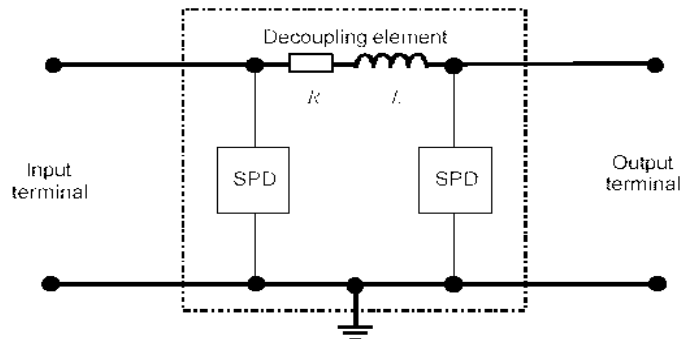


Fig.82 Coordination variant IV – Several SPDs in one element

g) Power distribution systems

Effective protection does not require SPD s to be installed in all the modes detailed. The following diagrams provide guidance on the selection and installation of SPDs on the more common distribution systems.

- **TN-C System**

A neutral and a protective earth conductor combine in a single conductor throughout the system. All exposed-conductive-parts are connected to the PEN conductor.

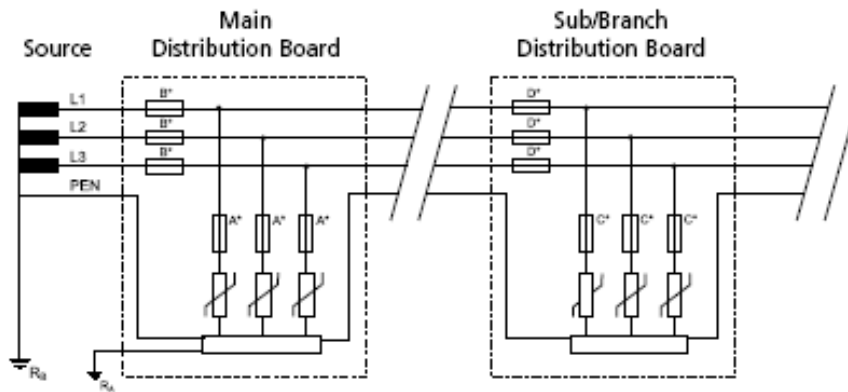


Fig.83 TN-C Distribution system

- **TN-S System**

A separate neutral and a protective earth conductor are run throughout. The protective PE conductor can be the metallic sheath of the power distribution cable or a separate conductor. All exposed-conductive-parts of the installation are connected to this PE conductor.

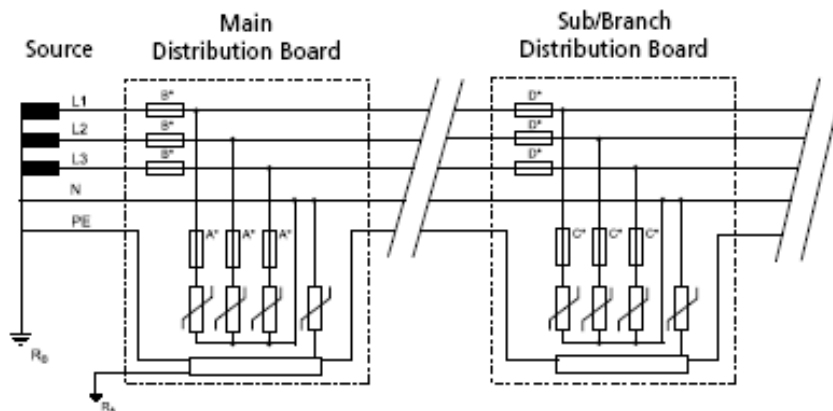


Fig.84 TN-S Distribution system

- **TN-C-S System**

A separate neutral and a protective earth combine in a single PEN conductor. This system is also known as a Multiple Earthed Neutral (MEN) system and the protective conductor is referred to as the Combined Neutral Earth (CNE) conductor. The supply PEN conductor is earthed at a number of points throughout the network and generally as close to the consumer's point-of-entry as possible. All exposed-conductive-parts are connected to the CNE conductor.

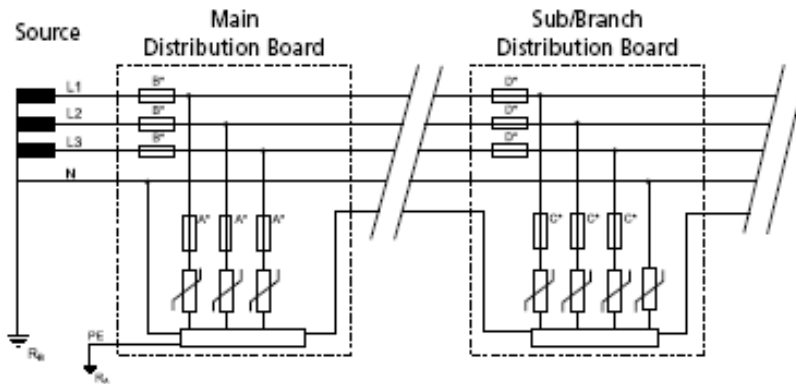


Fig.85 TN-C-S Distribution system

- **TT System**

A system having one point of the source of energy earthed and the exposed conductive parts of the installation connected to independent earthed electrodes.

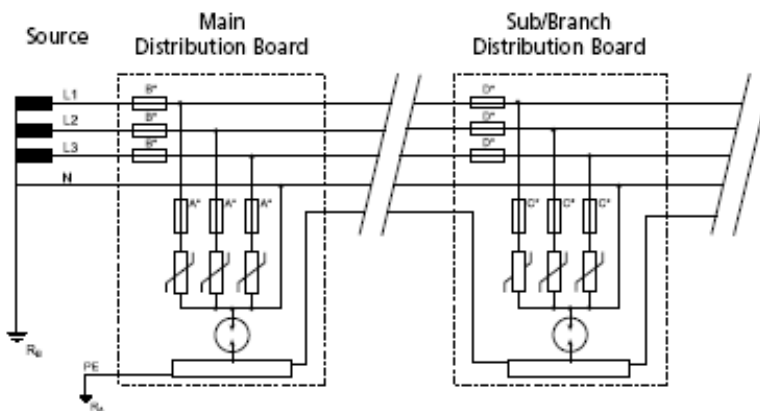


Fig.86 TT Distribution system

- **IT System**

A system having no direct connection between live parts and earth but all exposed-conductive-parts of the installation being connected to independent earthed electrodes

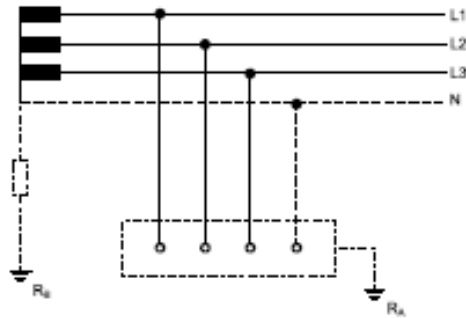


Fig.87 IT Distribution system

VI. Conclusion

Scientists still do not fully understand what causes lightning. Each year, thousands of homes and other properties are damaged or destroyed by lightning. Lightning is responsible for more deaths and property loss. Lightning can strike anywhere and do a lot of damage. Most of these tragedies can be prevented by adequate and proper protection measurements.

The International standard IEC 62305 presents the protection of structure, services and electrical and electronic system as an integral part of overall lightning protection scheme. Lightning protection measurements don't prevent lightning from striking; it provides a means for controlling it and preventing damage by providing a low resistance path for the discharge of lightning energy.

It's essential to evaluate the lightning electromagnetic environment in order to mitigate its effects and improve the power system quality.

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